PERFORMANCE APPRAISAL OF CRYO-TREATED TOOL BY TURNING OPERATION

Thesis Submitted in Partial Fulfillment of the Requirements for the Award of

Master of Technology

in

Production Engineering

By

Kalinga Simant Bal

Roll No: 210ME2295

Department of Mechanical Engineering

National Institute of Technology

Rourkela

2012

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Under the Guidance of

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CERTIFICATE

This is to certify that thesis entitled, “PERFORMANCE APPRAISAL OF CRYO-TREATED TOOL BY TURNING OPERATION” submitted by Mr. KALINGA SIMANT BAL in partial fulfillment of the requirements for the award of Master of Technology Degree in Mechanical Engineering with specialization in Production Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for award of any Degree or Diploma.

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Abstract

In the present investigation, PVD coated carbide inserts & uncoated carbide inserts were subjected to deep cryogenic treatment (-190°C) and machining studies were conducted on Stainless Steel using both untreated and deep cryogenic treated carbide cutting tool inserts. Micro-structural study, elemental characterization and crystallographic orientation were studied with the help of Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD) respectively. Micro-hardness of the same specimens was evaluated using Vickers micro-hardness. The results indicated that cryo-treatment resulted information of hard and wear resistant η-phase carbides along with the improvement of tungsten carbide distribution in cobalt binder phase in metal matrix. The turning tests were conducted at three different cutting speeds (50, 70, and 90 m/min), feed rate (0.04, 0.05, 0.06 mm/rev) and depth of cut (0.1, 0.2, 0.3 mm). The influence of cryo-treatment on carbide inserts were evaluated in terms of flank wear of the cutting tool inserts, surface finish of the machined work-pieces and cutting forces. The results showed that cryogenic treatment significantly improved the average flank wear. The surface finish produced on machining the work-piece is better with the deep cryogenic treated carbide tools than when compared with the untreated carbide tools. Cutting force for cryo-treated inserts appeared to be less than non- cryo-treated insert. Tool life test was also conducted and results favored cryo-treated inserts. Also, a comparative study was done between carbide inserts cryo-treated at different conditions. FEA analysis using ABAQUS software was carried out to investigate the stress and temperature distribution at tool-workpiece interface.

***Keywords- Cryo-treatment (CT), Carbide inserts,* Surface roughness, Cutting force, Flank wear**

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Introduction

MACHINING is a term that is related to removal of unwanted material, usually in the form of chips, from a workpiece. This process is used to convert preformed blocks of metal into desired shape, size and finish specified, often to great precision in order to fulfil design requirements. Hence, machining processes are often the most expensive. Although the theoretical analysis of metal cutting process is complex, but the application of these processes in the industrial world is widespread. The study of metal cutting focuses on the behaviour of tool and work piece material that influence the efficiency and quality of cutting operations. The metal cutting process involves pressing of a cutting tool against the workpiece, with certain degree of force, resulting in removal of material from the workpiece, in the form of chips. This results in enormous heat generation at the tool chip interface. Hence, continuous use of cutting tool for machining, results in tool wear eventually leading to its failure.

With the advancement in metal machining operations, it is necessary to identify and quantify micro-structural changes of metal alloys used in metal cutting processes. There are number of treatment processes used for different metals which cause them to behave differently under different conditions. However, the mechanism of micro-structural changes in alloys under various treatments, are not yet fully understood.

The use of thermal treatments to improve mechanical properties of metal components is an ancient art and is used until today. Many of the developed processes apply treatments in a range of temperature higher than room temperature. But, lately focus of researchers shifted towards the concept of sub-zero treatments and this was introduced to check the effect on industrial field.

Cryogenic treatment also known as cold or sub-zero treatment is a very old process and is widely used for high precision parts. The use of extreme cold to strengthen metals has been used since long time ago for centuries. For example, Swiss watch-makers use to store delicate components of their time pieces for several years in mountain caves to stabilize them in order to obtain maximum performance and precision. In general, unlike surface treatments, the cryogenic treatments influence the core properties of the materials.

The first attempts to perform sub-zero treatments were investigated at the beginning of the 20th century, but the use of cryogenic treatment (CT) to improve mechanical properties of materials has been developed from the end of the Sixties. Various studies have demonstrated that, the life of cutting tools like high speed steel (HSS) and tungsten carbide (WC) can be increased by cryogenic treatment.

Cryo-Treatment

Cryo-treatment (CT) is a supplementary process to conventional heat treatment, that involves deep freezing of materials at cryogenic temperatures (-190 °C) to enhance the mechanical and physical properties. The execution of CT on cutting tool materials increases wear resistance, hardness, dimensional stability, but at the same time, reduces tool consumption and down time for the machine tool set up, thus leading to cost reductions. The dry cryogenic process is precision controlled and the materials to be treated are not directly exposed to any cryogenic liquids. Overall, all the treated materials retain their size and shape. Cryogenically treated materials with some occasional heat treatment generally improve hardness, toughness, stability, corrosion resistance and reduce friction. Cryogenic treatment has been successfully applied to die and high speed steel (HSS), ferrous alloys and tungsten carbide.

Treatment Profiles

A fundamental distinction among different CT processes is given by the parameters of the cooling-warming cycle, and especially on the minimum temperature reached during the cycle. These are categorized as:

1. Shallow Cryogenic Treatment (SCT) or Subzero Treatment: the samples are placed in a freezer at -80 °C and then they are exposed to room temperature;
2. Deep Cryogenic Treatment (DCT): the samples areslowly cooled to -196 °C, held-down for many hours and gradually warmed to room temperature.

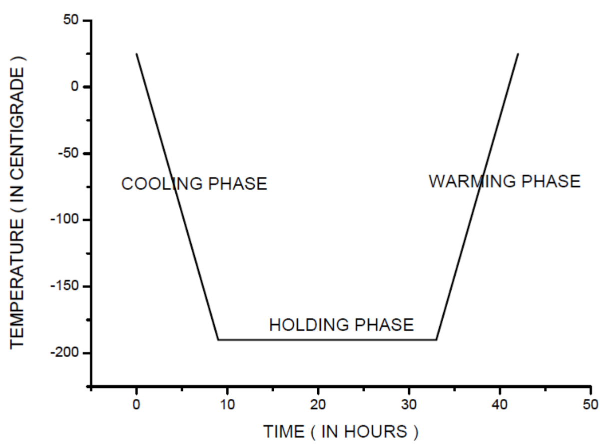


Fig. 1 Cryogenic Treatment temperature profile

Basic keynotes regarding cryo-treatment are listed below:

I. In some cases, the actual T_{min} could be higher than the nominal one because of thermal insulation limits;

II. Each new material needs to be treated and tested at different temperature levels (i.e. -190 °C, -130 °C and -80 °C), in order to identify optimum treatment conditions and investigation of micro-structural changes;

III. In most cases, Hold time of 24 hours are enough to obtain results and the same over 36 hours does not bring significant improvements;

IV. Cooling rate is one of the most critical parameter, which must not exceed 20-30 °C/h in order to prevent the rupture of the components because of the cooling stresses;

V. Warming rate is not closely controllable and little importance to this parameter despite of some suggested literature about carbides precipitation during the warming phase.

Cryogenic System

A cryogenic system is an equipment which allows controlling of temperature (i.e. cooling and heating rate), especially cooling in the cryogenic range in a chamber, using cryogenic fluid like liquid nitrogen or helium. During Sixties, CT was done by direct immersion into liquid nitrogen, which produced catastrophic result of cracking the components. But later, the cryogenic treatment system developed by Ed Busch (Cryo-Tech, Detroit, MI) in the late 1960's and later improved by Peter Paulin (300 Below Inc., Decatur, IL) with a temperature feedback control on cooling and heating rate, which prevented sudden temperature changes and lead to the development of efficient CT process.

The three types of cryogenic cooling systems commonly used are:

A. Gradual Immersion: The samples are immersed into the liquid nitrogen for a specific time, and then they are extracted and gradually led back to the room temperature by means of a flow of temperature controlled air;

B. Direct Nebulization: The liquid nitrogen is nebulized directly in the chamber and a fan allows to obtain homogeneous temperature distribution and the liquid nitrogen is dispersed around the samples;

C. Heat Exchanger: The liquid nitrogen flows through a heat exchanger and the output cooled gas is diffused inside the chamber by a fan. There is no contact between nitrogen and samples.

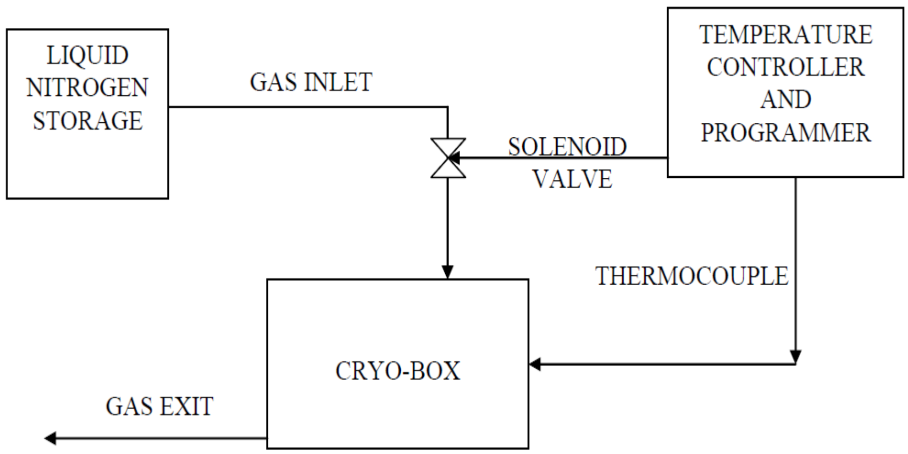


Fig. 2 Schematic representation of Cryo-treatment set-up

Out of above three processes, concept of third procedure of cooling system is generally used widely. Liquid nitrogen is allowed to flow from storage tank through inlet pipe and allowed to enter into cryogenic chamber (also called as Cryo-box). Temperature is controlled through computer programming software Delta T^{TM} and desired cooling rate can be set. The cooling effect is provided by LIN to the sample, but no direct contact is allowed between them. A fan is used for uniform distribution of temperature inside the chamber. After reaching the temperature set by programmer, thermocouple sends a signal to system controller through feedback mechanism, and hence, temperature controller regulates the flow of LIN in the chamber and stop further cooling. The LIN used gets converted and leaves the system as nitrogen gas.

Liquid nitrogen

Liquid nitrogen (abbreviated as LIN or LN or LN2) is nitrogen, which exists in a liquid state at a very low temperature, and is generally produced by fractional distillation of liquid air. Nitrogen was first liquefied at the Jagiellonian University by Polish physicists, Zygmunt Wróblewski and Karol Olszewskion 15 April 1883. It is non-toxic, odorless, colorless, inert and non-flammable. At atmospheric pressure, liquid nitrogen boils at −196 °C and is an efficient coolant. Hence, it is widely used as cryogenic fluid. But can lead to frostbite or cold burns (i.e. rapid freezing), when on contact with living tissue. Liquid nitrogen can be safely stored and transported invacuum flasks, usually called as “Dewar”. These vacuum flasks are appropriately insulated from external environment and perfectly sealed, as liquid nitrogen boils immediately on contact with a warmer object. This effect is generally known as the Leiden frost effect. As liquid nitrogen evaporates, it reduces the oxygen concentration in the air and act as an Asphyxiant. The liquid to gas expansion ratio of liquid nitrogen is 1:694; hence, the phase transition from liquid to gas can generate a lot of pressure very quickly and may result in an explosion.Vessels containing liquid nitrogen can cause violent oxidation of organic material. Despite of this violent nature, Liquid nitrogen has wide range of application in various fields such as cryogenic engineering; coolant for easier machining; freezing, storage and transport of food products; cryopreservation of biological sample; coolant for CCD cameras, superconductors, vacuum pumps traps; and cryotherapy.

Cutting Tool

A cutting tool is defined as a tool, which is used to remove material from the workpiece by means of shear deformation. The relative motion between the tool and the workpiece during cutting compresses the work material near the tool and induces a shear deformation, which produces chip. The chip passes over the rake face of the cutting tool and receives additional deformation because of the shearing and sliding of the chip against the tool. Cutting may be accomplished by single-point tool (i.e. turning, shaping) or multi-point tools (i.e. Milling, drilling). Cutting tools must be made of a material harder than the material which is to be cut, and also must be able to withstand the heat generated in the metal-cutting process. In order to have a longer tool life, all machining parameters have to be optimized.

The main purpose of cutting tool is to produce quality product within a specified time; therefore, it must have three basic characteristics:

- Hardness — to maintain strength at high temperatures;
- Toughness —to avoid chipping or fracture;
- Wear resistance — to have acceptable tool life.

Table 1 List of cutting tool commonly used

Tool Material	**Properties**	**Application**
Carbon tool steels	Unstable, very inexpensive, extremely sensitive to heat, hardness up to about HRC 65	Drill Bits, Taps, Dies, Hacksaw Blades, Reamers
High speed steel (HSS)	Unstable, inexpensive, retains hardness at moderate temperatures, hardness up to about HRC 67	Drill Bits, Taps
HSS cobalt	Unstable, moderately expensive, very resistant to heat, hardness up to about HRC 70	Milling Cutters, Drill Bits
Cast cobalt alloys	Stable, expensive, somewhat fragile, doesn't allow for high machining speed due to low hardness, rarely used, hardness	Turning Tool Bits

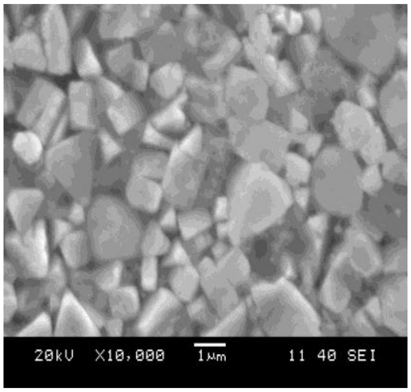
	up to about HRC 65	
Cemented carbide	Stable, moderately expensive, high resistance to abrasion, high solubility in iron, hardness up to about HRC 90	Turning Tool Bits, Milling Cutters, Saw Blades
Ceramics	Stable, moderately inexpensive, chemically inert and extremely resistant to heat, desirable in high speed applications, high fragility, hardness up to about HRC 93	Turning Tool Bits
Cermets	Stable, moderately expensive, cemented material based on titanium carbide, binder is usually nickel, provides higher abrasion resistance, more chemically inert, extremely high resistance to abrasion, hardness up to about HRC 93	Turning Tool Bits
Cubic boron nitride (CBN)	Stable, expensive, most fragile, high resistance to abrasion at the expense of much toughness, hardness higher than HRC 95	Turning Tool Bits
Diamond	Stable, very expensive, superior resistance to abrasion but also high chemical affinity to iron which results in being unsuitable for steel machining, extremely fragile	Turning Tool Bits, Coating on Tools

Carbide Insert

Cemented Carbides, also called Hardmetal or Widia, belong to a class of hard, wear-resistant, refractory materials in which the hard carbide particles are bound together by a soft and ductile metal binder. These materials were first developed in Germany in the early 1920s in response to demands for a die material having sufficient wear resistance for drawing tungsten incandescent filament wires to replace the expensive diamond dies then in use. It is a hard material used in machining tough materials where other tools would wear away. Carbide inserts provide better finish on the part, and allow faster machining. Carbide tools can also withstand higher temperatures than standard high speed steel tools. Tungsten carbide–cobalt (WC–Co) alloys consist of tungsten carbide grains surrounded by a cobalt base solid solution. The carbide grains impart hardness and wear resistance whereas metal binder cobalt imparts toughness. The wear resistance and fracture toughness of WC–Co alloys are inversely proportional to each other.

Depending on the required properties and application of the tool, the basic WC-Co material has been modified by mixing with a finely divided metallic binder (cobalt, nickel, or iron) or with additions of other cubic carbides, such as TiC, TaC, and NbC, to produce a variety of cemented carbides, which are used in a wide range of applications, including metal cutting, mining, construction, rock drilling, metal forming, structural components, and wear parts. Approximately 50% of all carbide production is used for metal cutting applications.

Cemented carbides are composed of a metal matrix composite where carbide particles act as the aggregate and a metallic binder serves as the matrix. The process of combining the carbide particles with the binder is referred to as sintering. During this process the binder eventually will be entering the liquid stage and carbide grains (much higher melting point) remain in the solid stage. As a result of this process, the binder embeds the carbide grains and thereby creating the metal matrix composite with its distinct material properties. The naturally ductile metal binder serves to offset the characteristic brittle behavior of the carbide ceramic, thus raising its toughness and durability.



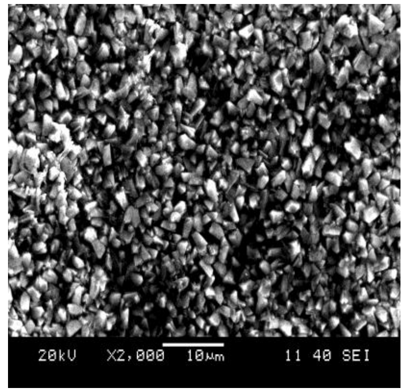


Fig. 3 Tungsten carbide particles (10,000×) Fig. 4 Tungsten carbide structure (2000×)

Coated carbides are widely used in the metal working industry and provide the best alternative for most turning processes. While machining the workpiece, carbide tools develop gradual wear on flank and rake face, thereby degrade the tool life. Cryogenic treatment has been acknowledged in several researches as a means of extending the tool life of many cutting tools. Studies on cryogenically treated (CT) cutting tools show micro-structural changes in the material that can influence the life of the tool significantly. The mechanisms responsible for the improvement in properties of tool steel by CT have also been well documented. Tungsten carbide is more efficient than HSS. But, the performance of cryogenically treated tungsten carbide inserts has not been fully studied. Some of the common applications of tungsten carbide tool are listed below.

Inserts for metal cutting

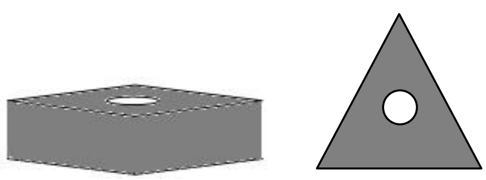


Fig. 5 Uncoated Tungsten carbide inserts

Carbide inserts are more brittle and expensive than other tool materials; therefore, the carbide cutting tip itself is often in the form of a small insert of different dimensions and shapes, fixed or clamped to larger shank made of carbon tool steel. It is used in turning tools, mining tools, tunnel cutting tools and endmills.

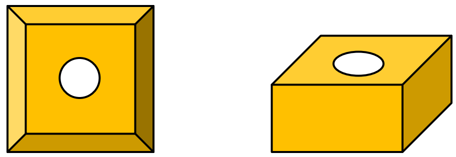


Fig. 6 Coated Tungsten carbide inserts

Due to brittle nature of carbide tip, they are sometimes coated with TiN (titanium nitride), TiC (titanium carbide), Ti(C)N (titanium carbide-nitride), and TiAlN (titanium aluminum nitride) using thermal CVD or mechanical PVD technique to increase the tool life. Coating improves hardness to the tool tip, aides towards easier machining and mainly helps to decrease the temperature generated during the machining process.

Industrial applications

Some key areas where cemented carbide components are used:

- Automotive components;
- Canning tools for deep drawing of two-piece cans;
- Rotary cutters for high-speed cutting of artificial fibres;
- Metal forming tools for wire drawing and stamping applications;
- Rings and bushings typically for bump and seal applications;
- Woodworking for sawing applications;

- Pump pistons for high-performance pumps;
- High performance nozzles for oil drilling applications;
- Roof and tail tools components for high wear resistance;
- Balls for ball bearings and ballpoint pens;
- Bridal jewelry industry;
- Rolls of rolling mills for both hot and cold rolling of tubes, bars, and flats.

Literature Review

The use of cryogenic treatment to improve mechanical properties of materials has been developed from the end of the Sixties. At the present time, the initial misunderstanding about CT has been cleared up and many literatures about different materials reporting laboratory tests results, micro-structural investigations and hypothesis on CT strengthening mechanisms have been published. The formation of fine dispersed η-carbides precipitation and Co binder densification has been widely observed and their effects on mechanical properties have been measured. The present work summarizes the state of art about CT, focusing on methods, parameters, results and assumed micro-structural mechanisms, in order to get a starting point for new researches to come.

Hollis et al., (1961) studied the effect of cryogenic cooling on the wear process of carbide-tipped tools while machining titanium. Authors introduced liquid CO_2 to the base of carbide insert through a capillary tube carried in tool shank so as to provide a low ambient temperature and increased temperature gradient through the cross-section of the tip. It was found that the proximity of low temperature heat sink retarded crater wear as welding and plucking action was significantly reduced.

Barron, (1982) showed that Cryogenic treatment has been successfully applied to die and high speed steel (HSS) ferrous alloys. The cryogenic process enhances the conversion from austenitic phase to martensite phase, which is a common change in ferrous metals as a result of heat treating and now cryogenic treating. The cryogenic treatment increases hardness and wear resistance of ferrous alloys.

Barron, (1982) subjected nineteen metals, including 12 tool steels, 3 stainless steels, and 4 other steels to cryogenic treatment to determine the difference between -84 ºC soak and -196 ºC soak in improving the abrasive wear resistant. The tool steels exhibited a significant increase in wear resistant after the soak at -196 ºC and a less dramatic increase after the -84 ºC soak. There was an increase in the wear resistant after the cryogenic treatment for the stainless steels, but the difference between the two treatments was less than 10 %. The plain carbon steel and the cast iron showed no improvement after either cryogenic treatment.

Cohen and Kamody, (1998) reported cryogenic treatment gradually reduces the tool temperature in an airtight refrigeration dry chamber to below −190 °C, after which the tool is slowly returned to room temperature.

Bryson, (1999) attributes the improved wear resistance, and hence the increase in tool life, of cryogenic treated carbide tools to the improvement in the holding strength of the binder after cryogenic treatment. The cryogenic treatment also acts to relieve the stresses introduced during the sintering process under which carbide tools are produced.

Arner et al., (2004) demonstrated that in a full production environment, the cryogenic treatment of tungsten carbide cutting inserts can have either a beneficial or detrimental effect on the tool life.

Stewart, (2004) applied cryogenic treatment to tungsten carbide and compared with untreated carbide to determine if tool wear could be reduced during turning tests with medium density fiberboard. Both the tool force data and observation of the cutting edges indicate that tool wear was reduced with cryogenic treatment. High-temperature oxidation was reported as the major contributor to the wear of tungsten carbide when machining medium density fibreboard.

Gallagher et al., (2005) studied the effect of cryogenic treatments on tungsten carbide tool life. Cryogenically treating tungsten carbide tooling has the capability of extending tooling life. As the number and size of the Eta phase increases, the tool life is reduced and vice-versa. The treatments also cause the gamma phase to become more evenly dispersed through reductions in vein and pocket size. The ability of the gamma phase to inhibit the alpha grain growth influences the tool hardness during cutting, thereby affecting the tool life.

Wang et al., (1996) presents a technique for machining advanced ceramics with liquid nitrogen (LN) cooled polycrystalline cubic boron nitride (PCBN) tool. A LN circulation system has been designed to control the cutting tool temperature. In this method the workpiece was not subjected to any preheating and hence the properties of the workpiece material i.e. Reaction Bonded Silicon Nitride (RBSN) are not altered before it enters the cutting zone. The temperature in the cutting zone has a significant influence on tool wear in the machining of ceramic with a PCBN tool. When the process was subjected to LN cooling, the tool wear of PCBNSO was less than without LN cooling. The wear on the tool was mainly attrition wear and abrasive wear. The surface roughness of the workpiece machined with LN cooling was much better than the surface roughness of the workpiece machined without LN cooling.

Abukhshim, (2006) presented the findings on the performance of CrTiAlN+MoST PVD coatings deposited by closed field unbalanced magnetron sputter ion plating [CFUBMSIP] in high speed machining of high strength alloy steel and reported the effect of these coatings on the tool-chip contact length and phenomena. The cutting tests were performed for a range of cutting speeds between 200 and 1200 m/min, thus covering conventional and high speed machining. The findings showed that, the tool chip contact length and hence, area available for heat flux transfer to the cutting tool reduces in conventional machining but significantly increases in high speed machining. The CrTiAlN+MoST coating were not found to significantly alter the contact length compared to the uncoated tool. Thus this coating has a capability to alleviate seizure for conventional cutting speeds.

Yong et al., (2007) primarily analysed the differences in tool performance between cryogenically treated and untreated tungsten carbide tool inserts during the high speed milling of medium carbon steel. In addition to dry cutting, machining with coolant was also tested. From this study, it has been noted that, the cryogenic treatment of tungsten carbide inserts improves tool life performance to a certain extent. This is largely dependent on the machining conditions and the length of machining time. Generally, longer machining times diminish any beneficial effect of tool life that cryogenic treatment brings about. High tool–chip interface temperatures have an adverse effect on the performance of cryogenically treated inserts. The cryogenically treated inserts performed better during wet machining, while untreated ones fared not much better than during dry machining. This suggests that lowering tool–chip interface temperatures might be beneficial to the performance of cryogenically treated tungsten carbide inserts.

Thakur et al., (2008) attempted to improve some of the mechanical properties of cemented tungsten carbide (WC) cutting tool by subjecting it to different post treatments and the response of WC–Co inserts to such different post treatments were evaluated in terms of micro-hardness, micro-structural changes, scanning electron microscope (SEM) micrograph and Co metal phase changes through XRD. Controlled cryogenic treatment improved the wear resistance. This is due to the densification of the cobalt metal binder which holds the carbide particles firmly and uniform distribution of tungsten carbide particles. XRD study showed formation of complex phases like W_3CO_3C andW_6CO_6C. These complex phases results in the increase in hardness.

Kumar and Choudhury, (2008) worked on experimental study of the effect of cryogenic cooling on tool wear and high frequency dynamic cutting forces generated during high speed machining of stainless steel. Experiments were carried out both in dry and cryogenic conditions as per design of experiments to understand the relative advantage offered by cryogenic cooling. It was found from the experimental results that, cryogenic cooling was effective in bringing down the cutting temperatures that attributed for the substantial reduction of the flank wear (37.39 %). Input parameters as speed, feed and depth of cut were correlated with output parameters, namely cutting force and flank wear through a regression equation. It was concluded that, cryogenic cooling is a possible answer for high speed eco-friendly machining. Also, consumption of liquid nitrogen was high, increasing the overall cost of machining.

SreeramaReddy et al., (2009) studied the effect of deepcryogenic treatment (-176 °C) on coated tungsten carbide ISO P-30 turning tool inserts. Machining studies were conducted on C45 workpiece using both untreated and deep cryogenic treated tungsten carbide cutting tool inserts. The machinability of the C45 steel workpiece is evaluated in terms of flank wear of the cutting tool insert, main cutting force and surface finish of the machined workpieces. Deep cryogenic treated carbide inserts were found to be better than that of untreated carbide inserts. Thus, it is seen that, subjecting tool to cryogenic treatment results in better machinability due to increase in thermal conductivity of the tungsten carbide, resulting in decrease in tool tip temperature during turning operation. The cryogenic treatment also results in better machinability due to increase in hot hardness of the tungsten carbide.

Vadivel and Rudramoorthy, (2009) analysed the effects of cryogenically treated carbide inserts for the machining operations on nodular cast iron for predicting the various performances, i.e. power consumption, surface roughness of work specimen and wear of the cutting tool inserts.

Coolant was used for the entire machining operation in order to emphasize that the life span of the cutting tool inserts and surface finish of the work specimen can be improved. The power consumption, surface roughness of work specimen, and wear of the cutting tool inserts were found to be favouring cryogenically treated coated carbide inserts. The SEM analysis also concludes that the wear resistance of cryogenically treated coated carbide inserts is higher than that of the untreated ones which is due to the presence of fine η-phase carbide distribution in the cryogenically treated inserts.

Singh and Singh, (2010) concluded that cooling rate is one of the most critical parameter, which must not exceed 20-30C°/h in order to prevent the rupture of the components because of the cooling stresses. The improvement in wear resistance and hardness by cryoprocessing is attributed to the combined effect of conversion of retained austenite to martensite and precipitation of η-carbides in case of tool steels. The phenomenon responsible for improved wear resistance in carbide cutting tools is the combined effect of increased number of η-phase particles and increase in bounding strength of binders used.

Ramji et al., (2010) aimed to examine the effect of cryogenic treatment of the coated carbide inserts and their performance in turning gray cast iron work pieces by selecting parameters such as tool wear, tool tip temperature, surface roughness of the work piece and cutting forces. Liquid nitrogen was selectively applied to the chip and the tool rake face in well controlled jet. Cryogenically treated inserts proved superior to the non-treated in all the test conditions in terms of lesser flank wear of the inserts and reduced surface roughness of the specimens. Finite element analysis showed that this cooling approach can bring the chip temperature down to the embrittlement temperature for the material. Consequently, it expands the chip-breaking range of feed and cutting speed, with a reduced chip–tool interface temperature and increased tool life. ANOVA indicated that, cryogenic treatment on carbide inserts was the only factor that influenced more, cutting velocity influenced tool tip temperature and cutting forces whereas depth of cut affected mainly on flank wear and surface roughness.

Ramji et al., (2010) aimed at examining the tool performance in terms of flank wear and surface roughness in turning of Gray Cast iron using design of experiments and SEM analysis. The extents of influence of cutting velocity, feed and the condition of the inserts were examined by conducting orthogonal array experimentation and responses obtained after turning were analysed. Cryogenic treatment of the inserts proved better than the non-treated ones in terms of less flank wear and better surface finish of Gray cast iron specimens. Cryogenic treatment can enable significant improvement in both productivity and product quality and hence overall machining economy offsetting the cost of cryogenic cooling.

Kalsi et al., (2010) reviewed various literatures to check how Cryogenic treatment (CT) of materials has shown significant improvement in their properties. He reported various advantages like reduced residual stresses, increase in hardness, increase in wear resistance, toughness, precipitation of carbides, eta-carbide formation, perfect homogenous crystal structure, better thermal conductivity and reduced chemical degradation was reported. Coating on cutting tools, and wet-cooling during machining, after CT of tools, are the other suggested methods to improve the tool life further.

Chen et al, (2011) conducted an experiment and finite element (FE) simulation to study the cutting forces, cutting temperature and tool wear mechanism during high speed dry turning of 26NiCrMoV145 using multilayer TiCN+Al2O3 coated carbide inserts. SEM analysis reported crater wear and coating peeling at every cutting speed. Flank face wear appears smooth when cutting speed increases.

Experimental Layout

Experimental Layout is divided into following steps:

1. Cryo-treatment Procedure
2. Pre- machining SEM, EDS, XRD Study
3. Performance evaluation by turning operation
4. Post- machining SEM study for tool wear
5. Taguchi analysis
6. Hardness test
7. Conductivity test

I. Cryo-treatment Procedure

a) Cryogenic setup

The Kryo 360-1.6 is simple to programme and operate, which incorporates all of the critical features expected from a high class biological freezer with the most advanced cryopreservation techniques. The controlled rate of cooling and heating ensures sample integrity during transfer to storage. The high capacity LNP4 active nitrogen pump offers both faster cooling rates and a large reservoir, along with extended hold time. Compact design, controller displays demand, sample and chamber temperatures, programme stage and current temperature graphic are some of the unique features of the device.

Table 2 System Specifications of Kryo 360-1.6 cryogenic chamber

Operating Range	+40.0ºC to -180ºC
Heating rates	0.01ºC/min to 10ºC/min
Cooling rates	-0.01ºC/min to -50ºC/min
Chamber Capacity	1.7 lts
Chamber dimensions (mm)	Internal 200 x Ø150 External 450 high x 300 wide x 420 deep
PC Software	Delta T™

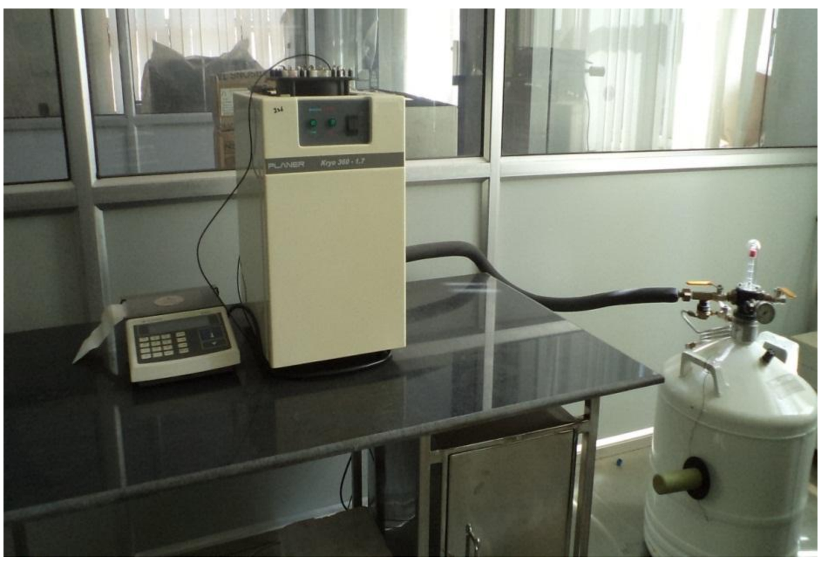


Fig. 7 Kryo 360-1.6 LIN cryogenic treatment set up

b) Experimentation

Experiment was carried out in cryogenic treatment set up namely Kryo 360-1.6. LIN used for this purpose was stored in the transport storage tank. Cryogenic chamber was started and LIN was delivered at required pressure and all safety valves and pipelines or transfer lines were checked properly, if correctly sealed or not. Cooling rate was set up by using computer controlled program at 0.5 °C/min and temperature was set to move from 25 °C to -190 °C. Inserts were properly cleaned. As temperature of cryogenic chamber reached 25 °C, inserts were carefully kept inside and the chamber was closed. After 8 hrs., when temperature reached -190 °C, the thermocouple generated a signal to programmer to stop further cooling automatically through solenoid valve which controls LIN supply. It was left for soaking at -190 °C for 24 hrs. It was then brought to room temperature at the same rate (i.e. 0.5 C/min) by warming. This process of warming is called tempering. After being brought to room temperature, insert is kept in open environment before being transported to furnace regarding further tempering. Inserts were kept inside the furnace and machine was started. The temperature was set to move from 25 °C to 200 °C. This process exactly took 1 hr. Inserts were held at 200 °C for 3 hrs. and then slowly cooled down to room temperature in controlled environment. So, the total duration of cryogenic process is 45 hrs.

Similarly, cryogenic treatments was carried out for other set of inserts at 1.0 °C/min in order to check the effect of different rate of cryogenic cooling on micro-structure and performance of inserts and also compare with non-CT inserts.

i. Cryo-treatment at 0.5 °C/min (Cryo-treated + tempered)

The cool down time is 8 hours. A temperature of –190 °C is achieved in 8 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 8 hours known as the warm up temperature. The total duration of the cryogenic treatment is about 40 hours. After the material is cryogenic treated, it is tempered to 200 °C and the same is achieved in 1 hour and it is kept at this temperature for 3 hours. The material is brought back to room temperature in the next 1 hour. The total duration of tempering cycle is 5 hours. Tempering is done in order to remove the stresses developed during cryogenic cooling. The total duration of the Cryogenic-tempering cycle is 45 hours.

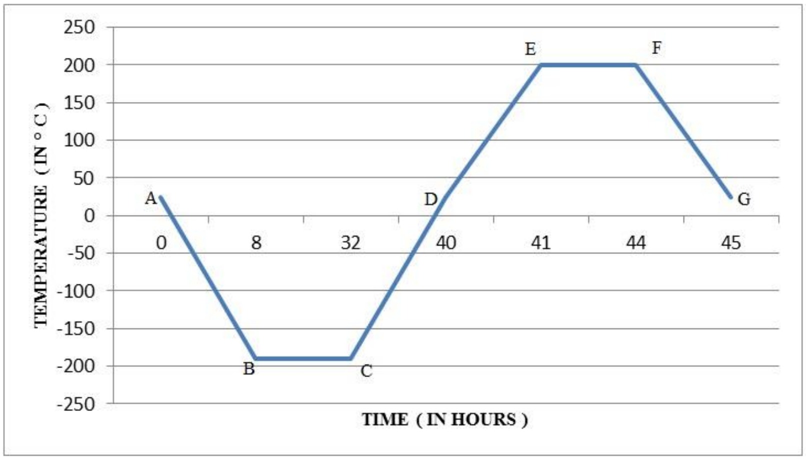


Fig. 8 Graph for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

Process A-B: Cooling phase (Chilling)

Process B-C: Soaking phase

Process C-D: Warming phase

Process D-E: Tempering phase

Process E-F: Holding phase

Process G-H: Cooling phase

ii. Cryo-treatment at 1.0 °C/min (Cryo-treated + tempered)

The cool down time is 4 hours. A temperature of –190 °C is achieved in 4 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 4 hours known as the warm up temperature. The total duration of the cryogenic treatment is about 32 hours. After the material is cryogenic treated, it is tempered to 200 °C and the same is achieved in 1 hour and it is kept at this temperature for 3 hours. The material is brought back to room temperature in the next 1 hour. The total duration of tempering cycle is 5 hours. Tempering is done in order to remove the stresses developed during cryogenic cooling. The total duration of the Cryogenic-tempering cycle is 37 hours.

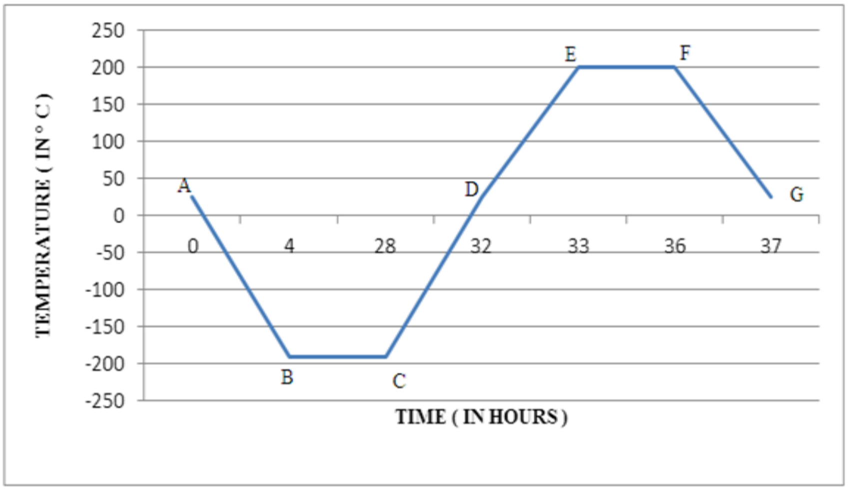


Fig. 9 Graph for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

iii. Cryo-treatment at 1.0 °C/min (Cryo-treated)

The cool down time is 4 hours. A temperature of –190 °C is achieved in 4 hours. After cooling down, material is soaked at this minimum temperature for 24 hours. It is again brought up to the room temperature in 4 hours known as the warm up temperature. The total duration of the cryogenic treatment is about 32 hours. No tempering is done.

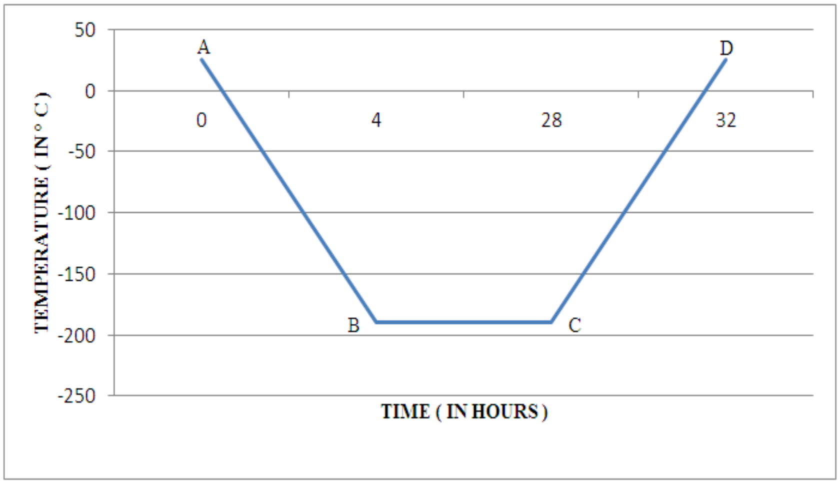


Fig. 10 Graph for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

Fig.11 Tempering Machine

Table 3 Various CT procedures used

Cryo-treatment Condition	**Cool Down Time(in hrs)**	**Soaking Time (in hrs)**	**Warming Time (in hrs)**	**Tempering Time (in hrs)**	**Holding Time (in hrs)**	**Cooling Time (in hrs)**	**Total Treatment Time**
0.5 °C/min	8	24	8	1	3	1	45
1.0 °C/min	4	24	4	1	3	1	37
1.0 °C/min	4	24	4	-	-	-	32

II. Physical Characterization

a) Scanning electron microscopy (SEM)

SEM is used to examine surface features, textures and particles that are too small to see with standard optical microscopes. The JSM-6480LV is a high-performance, scanning electron microscope with a high resolution of 3.0 nm. The fully automatic low vacuum system allows observation of specimens which cannot be viewed at high vacuum due to excessive water content or due to a non-conductive surface. Its asynchronous five-axis stage rotation and tilt can accommodate a specimen of up to 8-inches in diameter. Standard automated features include auto focus, auto gun and automatic contrast and brightness, which provide fast and unattended data acquisition.

Fig. 12 JEOL JSM-6480LV Scanning Electron Microscopy

All samples are analyzed using a JEOL JSM-6480LV SEM with an Oxford INCA X-sight EDXA (Energy Dispersive X-Ray Analysis system).

b) Energy Dispersive X-ray Spectroscopy (EDS)

Energy Dispersive X-ray Spectroscopy (EDS) provides micro-chemical information from a sample inside a Scanning Electron Microscope (SEM). A sample with unknown chemistry is analysed and spectra, elemental distribution maps and quantified chemistry is produced. Electron Backscatter Diffraction (EBSD) provides micro-structural information from a sample inside an SEM. A sample of known chemistry is analysed and maps of micro-structure, plots of orientation frequency, phase % and grain size are produced using Point and Shoot Phase Identification.

c) X-ray diffraction (XRD)

X-ray diffraction (XRD) is a versatile, non-destructive technique that reveals detailed information about the chemical composition and crystallographic structure materials. When a monochromatic X-ray beam with wavelength lambda is projected onto a crystalline material at an angle theta, diffraction occurs. Based on the principle of X-ray diffraction and the concept of Bragg's Law conditions, the structural, physical and chemical information about the material investigated can be obtained.

Fig.13 X-ray Diffraction Machine

III. Performance Evaluation by Turning Operation

In order to check which tool is best, inserts were machined with AISI 304 Stainless Steel by turning operation. Regression equation was used to correlate input parameters as speed, feed and depth of cut with output parameters, namely surface roughness, flank wear and cutting force.

Table 4 Experimental Conditions for Turning

Lathe	NH 26 Precision Lathe
Work specimen material	AISI 304 Stainless Steel
Cutting tool	1. PVD coated Tungsten Carbide P 30 Insert 2. Uncoated Tungsten Carbide P 30 Insert
Insert Designation	SNMG 120408
Tool Holder	PSBNR 2525 M12
Tool Geometry	-6°, -6°, 6°, 6°, 15°, 75°, 0.8
Cutting Velocity	50, 70, and 90 m/min
Feed	0.04, 0.05, 0.06 mm/rev
Depth of cut	0.1,0.2,0.3 mm
Type	Dry cutting
Force Measuring Dynamometer	Kistler Type 9272 SN 1634808
Surface Roughness Measurement	Taylor Hobson Pneumo Surtronic 3+
Flank Wear Measurement	Optical Microscope

a) Lathe

NH 26 Precision Lathe is used for turning AISI 304 Stainless Steel with Tungsten Carbide Insert as tool. Its rigid rectangular section with wide bed along with short spindle and shaft for maximum drive rigidity power provides precision and versatility for achieving unmatched capabilities in precision turning.

Table 5 Specification of NH 26 Precision Lathe

Distance between centers	3000 mm
Spindle Speed range	16 from 40-2040 forward 7 from 60-1430 reverse
Spindle power	11 kW
Feed range (longitudinal)	0.04-2.24 mm/rev
Main motor power	7.5 kW

Fig.14 NH 26 Precision Lathe

b) Work Specimen Material

i. Chemical Composition

Table 6 Chemical Composition of AISI 304 grade austenitic stainless steel

Element	C	Cr	Ni	Fe	Mn	P	S	Si	N
Content (%)	0.08	18-20	8-10.5	66.354-74	2	0.045	0.03	1	0.1

ii. Physical Properties

Table 7 Physical Properties of AISI 304 grade austenitic stainless steel

Density	8 gm/cm^3
Hardness	29 HRC

iii. Mechanical Properties

Table 8 Mechanical Properties of AISI 304 grade austenitic stainless steel

Elastic Modulus	197 GPa
Elongation % (Break Point)	70% (upto 50 mm)
Shear Modulus	86 GPa

c) Cutting Tool

Tungsten carbide inserts are used for machining AISI 304 austenitic stainless steel, which are categorized below:

1. PVD coated Tungsten Carbide P 30 Insert
2. Uncoated Tungsten Carbide P 30 Insert

d) **Insert Designation**

1. SNMG 120408 TN 4000 08 (PVD coated Tungsten Carbide P 30 Insert coated with TiCN + Al2O3 + TiN),
2. SNMG 120408 TTR 08 (Uncoated Tungsten Carbide P 30 Insert)

e) **Tool Geometry**

Both inserts differ only on the basis of coating, but have same tool geometry.

Table 9 Tool Geometry of insert

Inclination angle	-6˚
Orthogonal rake angle	-6˚
End clearance angle	6˚
Side clearance angle	6˚
Auxiliary cutting edge angle	15˚
Principal cutting edge angle	75˚
Nose radius	0.8 mm

f) **Tool Holder**

PSBNR 2525 M12 is a right hand tool holder used to turning operation.

g) **Surface Roughness Measurement**

The Taylor Hobson Pneumo Surtronic 3+ Talysurf is ideal instrument for measurement of surface roughness of various types of components, even if they are inaccessible or difficult to move. Features like portable and flexible; simple menu structure; long traverse length and extended pick-up reach; powerful software option; comprehensive range of accessory & pick-up reach along with good mechanical rigidity, makes it a unique device for surface finish measurement.

Fig.15 Taylor Hobson Pneumo Surtronic 3+

Table 10 Specification of Taylor Hobson Pneumo Surtronic 3+Talysurf

Traverse length	120 mm
Straightness of traverse	1.0 micron
Traverse speeds	1.0 mm / sec and 0.5 mm/sec (+/- 5%)
Column traverse	450 mm
Stylus range	6 mm
Stylus tip radius	1.5 - 2.5 micron

h) Force Measuring Dynamometer

Four-component Kistler Type 9272 SN 1634808 Dynamometer is used for measuring torque and the three orthogonal components of a force. The dynamometer has a great rigidity and consequently a high natural frequency. Its high resolution enables the smallest dynamic changes in large forces and torques to be measured. The dynamometer is rustproof and protected against penetration of splash water and cooling agents.

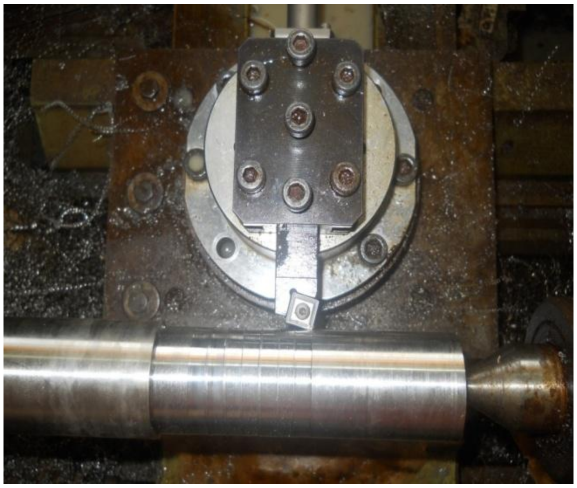


Fig.16 Kistler Type 9272 SN 1634808 Dynamometer

Fig.17 Kistler Type 9272 SN 1634808 Dynamometer Monitor Display

Table 11 Specification of Kistler Type 9272 SN 1634808 Dynamometer

Measuring range	F_x, F_y: 5kN F_z: 20kN
Operating temperature range	0-70°C
Height	70 mm
Diameter	100 mm
Sealing	Welded/epoxy (IP67) with connecting cable types 1677A5, 1679A5
Mass	4.2kg

IV. Turning Operation

Fig. 18 Experimental set up for turning

To check the effect of CT, inserts were subjected to turning operation and compared with non-CT insert. Workpiece was taken as AISI 304 Stainless steel and turning operation was carried out on NH 26 Precision Lathe. Machining parameters like cutting speed, feed rate and depth of cut were taken as input and performance of different inserts were analyzed on basis of flank wear of insert, surface roughness of machined workpiece and cutting forces generated during machining. Using input parameters a Taguchi L9 experimental run was designed using DOE Minitab software and experiment was conducted for both types of inserts, each run having duration of 60 seconds. Consecutively, dynamometer was fixed on the tool post and cutting forces were recorded. Also, surface roughness was measured using Talysurf and flank wear was measured using optical microscope. The results were analyzed using Taguchi DOE in order to find out the individual effect of input parameters on various output responses.

Fig. 19 Optical Microscope

V. Mechanical Characterization

a) Hardness Test

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a test force of between 1gf and 100kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surfaces of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

The Vickers number (HV) is calculated using the following formula:

$$HV = 1.854(F/D2),$$

where F is the applied load (in kgf) and D2 the area of the indentation (in sq. mm).

b) Conductivity Test

The four point probe is a simple apparatus for measuring the resistivity of samples at various temperatures with a high degree of accuracy. Because of the use of pressure contacts, this arrangement is specifically useful for quick measurement. It includes the four probes arrangement, PID controlled oven, constant current source, and DC micro-voltmeter. The four point probe contains four thin collinearly placed tungsten wires probes, which are made to contact the sample under test. Current is made to flow through two outer probes, and voltage is measured between the two inner probes, ideally without drawing any current, hence, allows the measurement of the substrate resistivity. After obtaining resistivity, conductivity is calculated for the specimen.

Results and Discussion

I. SEM Analysis

SEM analysis was carried out in order to study the micro-structure of Cryo-treated and non Cryo-treated inserts in order to check the effect of Cryo-treatment.

SEM analysis include

a) Micro-structural analysis

b) Tool wear analysis

a) Micro-structural Analysis

Microstructure analysis is carried out to understand the micro-structural changes that provide the information about improvement in properties such as hardness and wear resistance. According to the procedure specified in ASTM standards B657 'Standard method for metallographic determination of microstructure in cemented tungsten carbides', metallographic microstructure was determined. The following phases are generally present in the metallographic microstructure of cemented tungsten carbides:

a. Alpha (α-phase): Tungsten carbide (WC),

b. Beta (β-phase): Cobalt binder,

c. Gamma (γ-phase): Carbides of cubic lattice (TaC, TiC, NbC, WCetc.) and

d. Eta (η-phase): multiple carbides tungsten and at least one metal binder ((Co_3W_3C (M_6C), Co_6W_6C ($M_{12}C$))

The α-phase comprises of tungsten carbide grains which is gray angular shaped grains. The β-phase consists of white vein like regions which is cobalt binder phase, and this imparts toughness to the cutting insert. The eta η-phase carbide appears as dark gray specksand are formed during the long exposure to critical temperatures, which occupies the volume formerly occupied by cobalt. Eta η-phase is a carbon deficient form of tungsten carbide, which results in a harder, more brittle cemented carbide part. These fine η-phases in addition to the larger carbide particles present before thermal treatment, along with homogeneously distributed Co binder, form a denser, uniform and tougher metal matrix.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

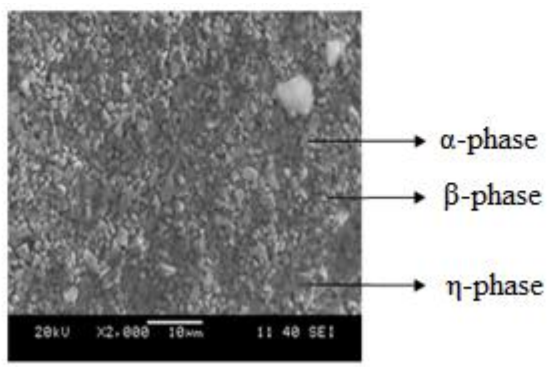


Fig. 20 SEM image for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

After SEM analysis of above insert, it was found that, due to CT and tempering, the concentration of η-phase of carbide increased and were uniformly distributed along the metal matrix. Also, the concentration of α-phase consisting of WC increased along with Co binder. This proved that, after CT and tempering, the hardness of insert increased due to η-phase and toughness is increased due to Co binder densification.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

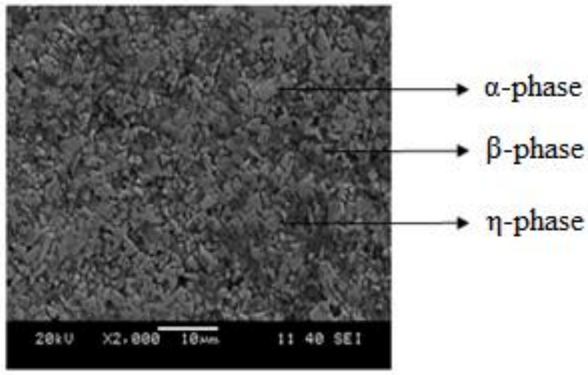


Fig. 21 SEM image for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

Since, treatment at 1˚C/min disobeys CT laws, but still, it was found that, CT caused an increase in concentration of WC while causing simultaneous decrease in concentration of Co binder. Both these concentration are less than that of above CT condition (i.e. 0.5 ˚C/min). Also, SEM study showed non-uniform distribution of almost all phases like WC, Co binder, γ-phase and η-phase as micro-structural grain refinement could not take place even after tempering.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

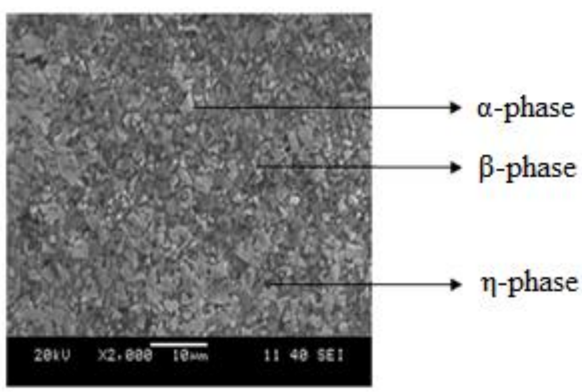


Fig. 22 SEM image for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

SEM study showed an abrupt increase in concentration of WC, but also simultaneous decrease in Co binder phase, which clearly indicates that, only CT of insert is not sufficient to improve the toughness. The insert hardness might have increased and could possibly make it prone to chipping during machining. The decrease in Co binder phase and its non-uniform distribution along metal matrix is due to only CT and without tempering. Some traces of η-phase carbide were found, but acceptable grain refinement had not taken place.

iv. Non Cryo-treated insert

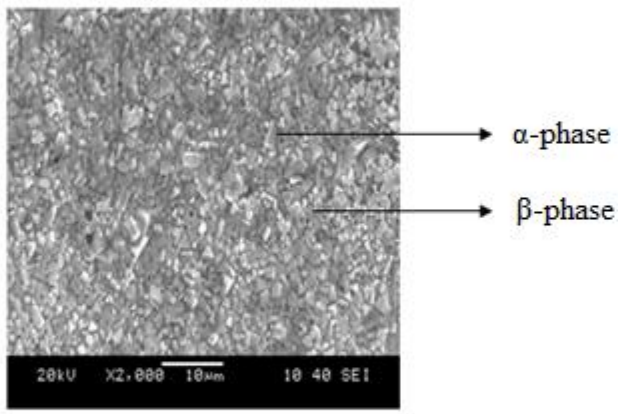


Fig. 23 SEM image for Non Cryo-treated insert

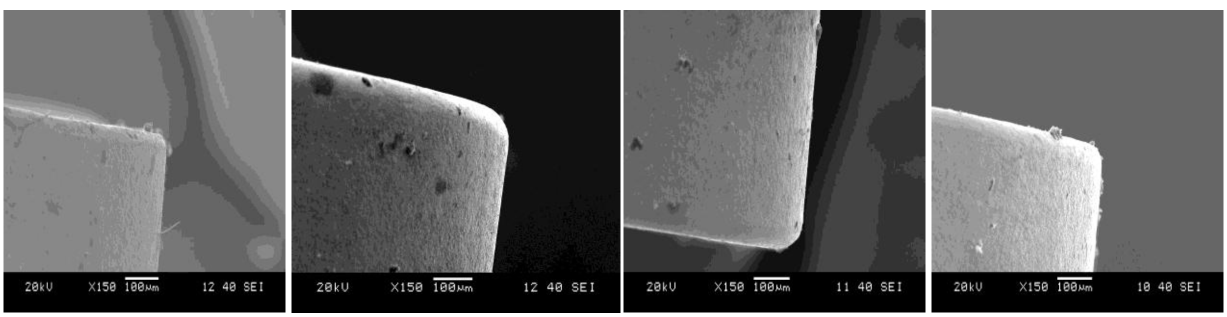
Since, this carbide insert was used as comparison to other above inserts treated at different cryogenic condition, we can conclude from SEM analysis that, WC, Co binder and Carbides of cubic lattice (TaC, TiC, NbC, WC etc.) were uniformly distributed in non Cryo-treated insert.

It is seen clear that due to CT, some physical changes had takenplace. During cryogenic treatment, coarser and randomly distributed η phaseparticles are refined into the most stable form presence of more and fine η-phase carbides, while in case of untreated inserts, fewer and coarser η-phase carbides was observed. Micro-structural analysis also reported densification of cobalt binder, which holds the carbide particles more firmly in metal matrix thereby, enhancing the wear resistance and hardness of the insert, along with improvement in toughness property. The micro-stresses in the cutting inserts are also relieved, which increase the tool life.

b) Tool Wear Analysis

The cutting tools while machining, particularly in continuous chip formation processes like turning, generally fail by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc., depending upon the tool-workpiece and machining condition. Tool wear initially starts with a relatively faster rate due to a break-in wear caused by attrition and micro-chipping at the sharp cutting edges. In this work, SEM analysis is carried out to understand the flank wear forcryogenically treated and untreated tool inserts for one setof cutting conditions.

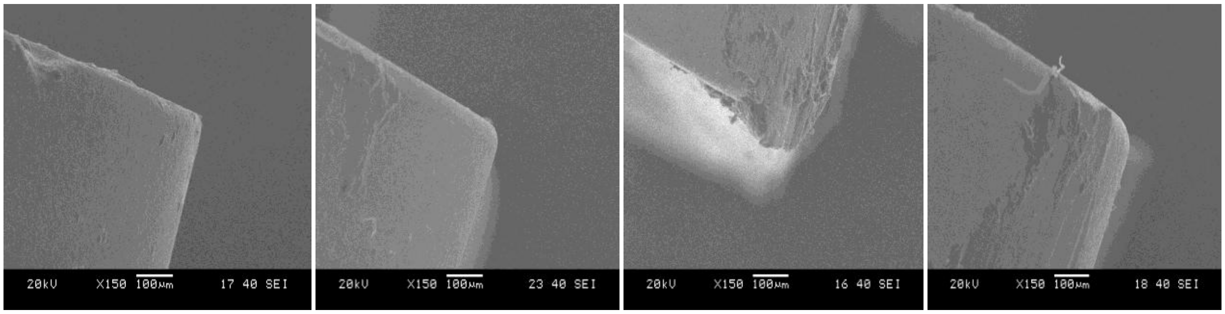
i. Pre-Turning Tool Wear Study



(a) (b) (c) (d)

Fig. 24 Pre-Turned SEM image for Cryo-treated insert at (a) 0.5 °C/min (Cryo-treated + tempered), (b) 1.0 °C/min (Cryo-treated + tempered), (c) 1.0 °C/min (Cryo-treated), (d) Non Cryo-treated insert.

ii. Post-Turning Tool Wear Study



(a) (b) (c) (d)

Fig. 25 Post-Turned SEM image for Cryo-treated insert at (a) 0.5 °C/min (Cryo-treated + tempered), (b) 1.0 °C/min (Cryo-treated + tempered), (c) 1.0 °C/min (Cryo-treated), (d) Non Cryo-treated insert

When comparison of tool wear was made before and after turning with AISI 304 stainless steel for various insert, it was found that,

- Less wear occurred in case of insert CT at 0.5 °C/min, when followed by tempering;
- Appreciable wear occurred for insert CT at 1.0 °C/min along with tempering;
- Chipping of tool tip was observed for insert only CT at 1.0 °C/min;
- Tool wear found to be more in case in non-CT inserts than CT inserts.

Since the cryogenic treatment improves the hardness of the coated inserts, it provides more wear resistance that reduces the flank wear.

To support the above conclusion, it was necessary to cross check the results with EDS analysis which would provide the weight percentage of various phases present in the carbide inserts and would aid to reach an agreeable conclusion with SEM results.

II. EDS Analysis

EDS analysis is carried out in order to support the conclusion drawn from micro-structural image of carbide insert using SEM.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

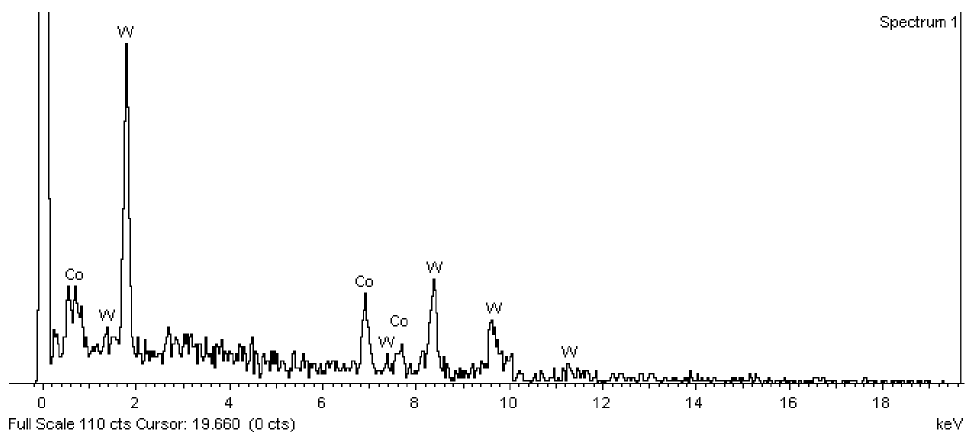


Fig. 26 EDS for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

Above EDS analysis showed a greater increase in concentration in carbide (i.e. η-phase) which proved an increase in hardness of insert. Also, concentration of Co binder phase increased, which concludes that, CT and tempering increases the toughness and conductivity. It is also observed that, no carbon percentage in present, which could possibly be due to conversion of all primary carbides into η-phase carbides.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

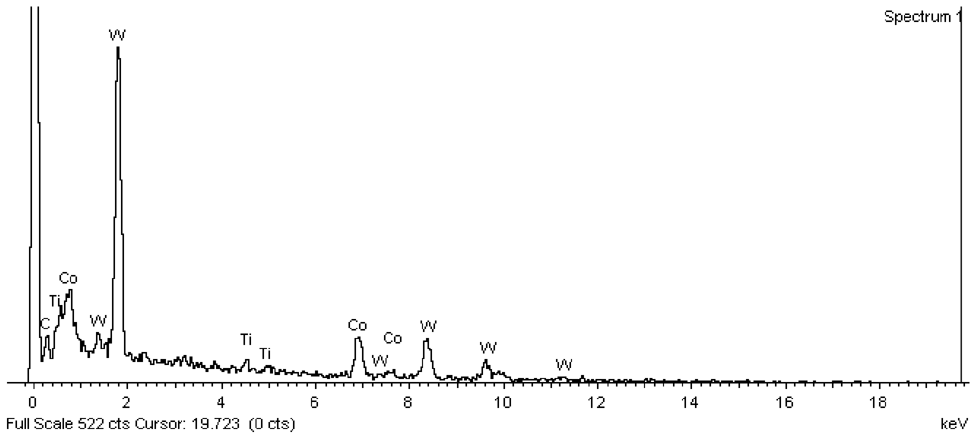


Fig. 27 EDS for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

Less amount of tungsten carbide and Co phase was observed after EDS analysis. This might be attributed to as inability of precipitation due to high rate of CT (i.e. 1.0 ˚C/min). Also, Carbon weight percentage is high, which proves less conversion of primary carbides into secondary phase carbides had occurred. Proper densification of Co binder phase could not take place.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

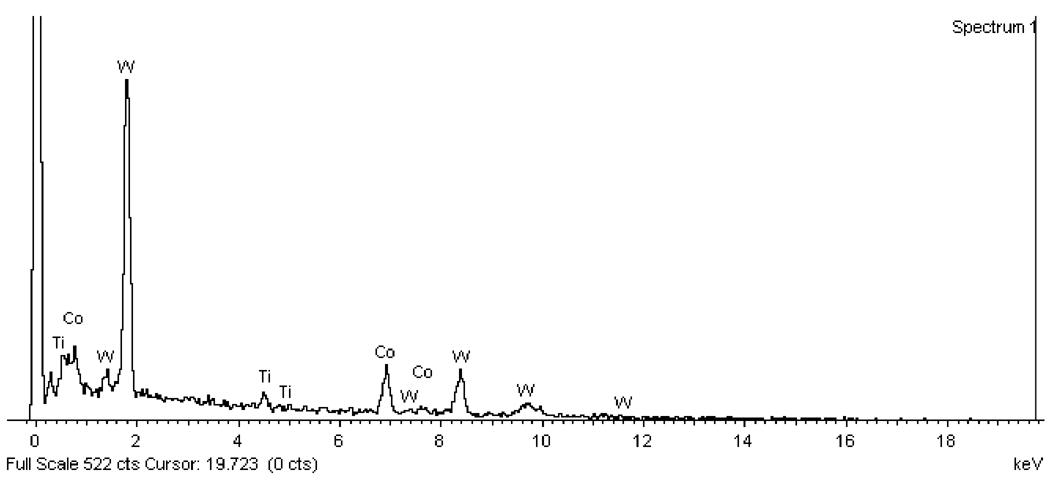


Fig. 28 EDS for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

EDS analysis for this insert showed an increase in carbide phase, but also simultaneous decrease in Co binder phase, which conclude that, toughness of this insert might be decreased due to less grain refinement of Co phase in metal matrix, which could have been avoided, if CT would have been followed by tempering. Due to high content of WC % and low Co %, insert becomes brittle and is prone to fracture.

iv. Non Cryo-treated insert

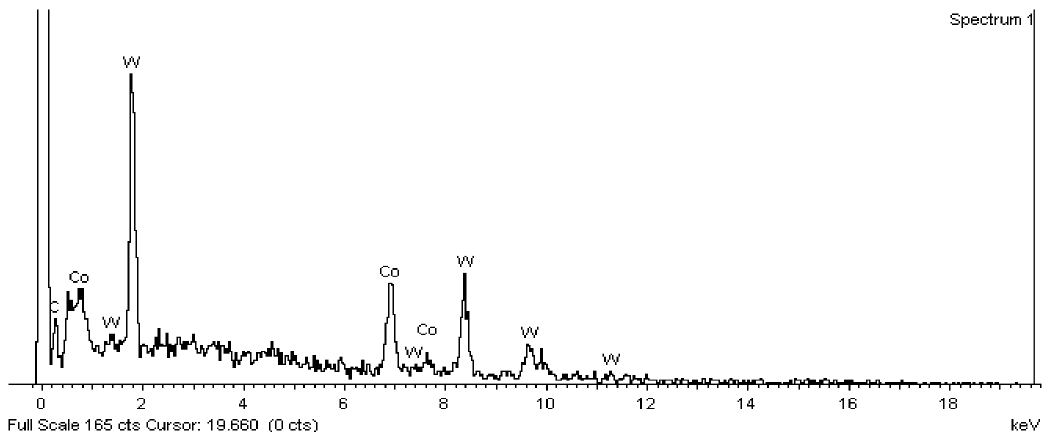


Fig. 29 EDS for Non Cryo-treated insert

Since, this category of insert is non-CT and not tempered, it is taken as basis for comparison with other CT inserts. As usual, its EDS analysis showed a uniform distribution of WC in Co binder along with some traces of primary carbide particle.

Comparison Study

Table 12 Composition of various elements present in different insert type

Cryo-treatment Condition	WC (Weight %)	Co (Weight %)	Carbide (Weight%)
0.5 °C/min (CT+T)	72	28	-
1.0 °C/min (CT+T)	64	14	21
1.0 °C/min (CT)	80	17	-
Non CT	47	23	31

III. XRD Analysis

Tungsten carbide inserts were examined to understand whether any structural changes have taken place or not after treating WC inserts using X-ray diffraction method. Cryogenic treated inserts showed almost same trend as that of an untreated insert because due to cryogenic treatment only physical changes takes place. Densification of the cobalt metal binder might have taken place.

i. Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

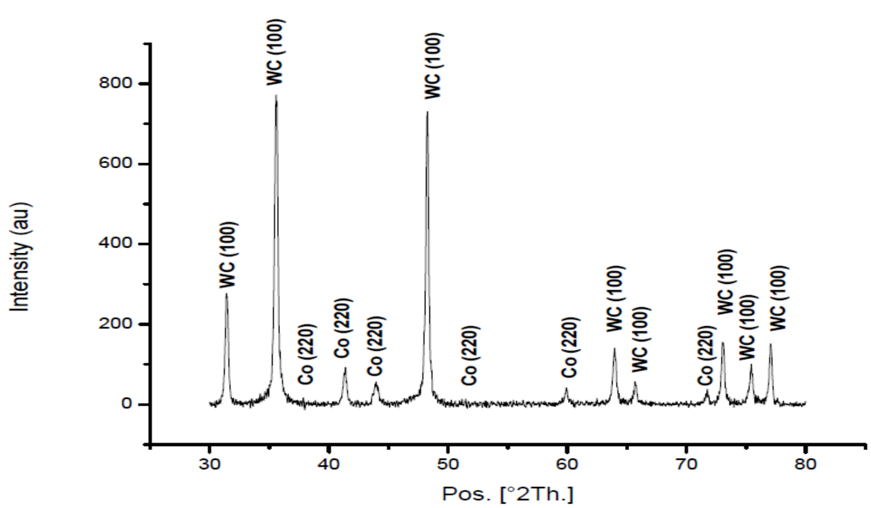


Fig. 30 XRD Profile for Cryo-treated insert at 0.5 °C/min (Cryo-treated + tempered)

This CT insert when analyzed by XRD showed presence of WC crystal along with Co uniformly distributed in metal matrix. Also, on further analysis, presence of other forms of carbides were found to be low as compared to others, which concludes that due to CT and tempering, most of primary carbides are converted to secondary η-phase carbides, which improves the tool life due to increase in hardness along with toughness.

ii. Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

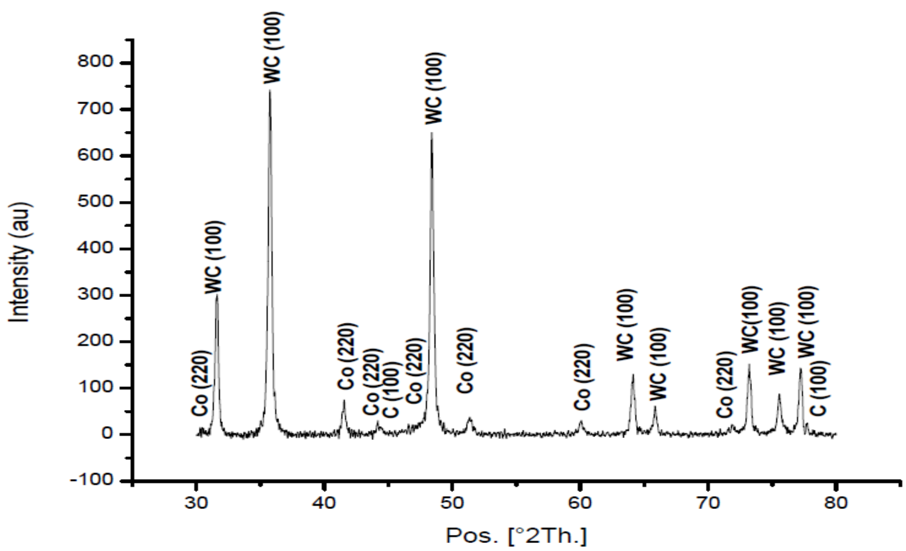


Fig. 31 XRD Profile for Cryo-treated insert at 1.0 °C/min (Cryo-treated + tempered)

XRD analysis of this insert showed presence of primary carbide, which points to the direction that, less η-phase are formed. This is due to high cooling rate, which led to non-homogeneous grain refinement of carbide particles. Although, Co binder densification reduced, but insert might have acceptable harness property due to presence of WC, which is solely due to tempering performed after CT.

iii. Cryo-treated insert at 1.0 °C/min (Cryo-treated)

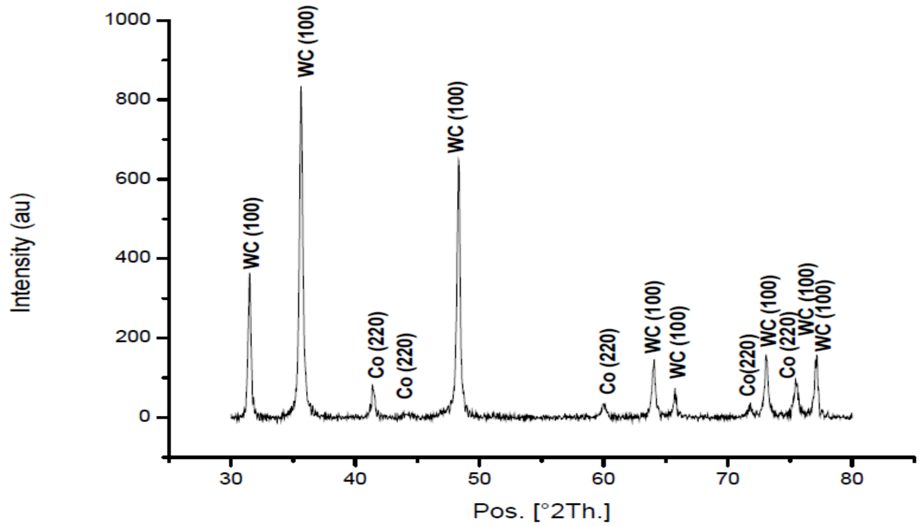


Fig. 32 XRD Profile for Cryo-treated insert at 1.0 °C/min (Cryo-treated)

XRD analysis of this insert showed presence of WC crystal but simultaneous decrease in quantity of Co and increase in quantity of primary carbides, which leads to conclusion that, due to only CT and no tempering being done, conversion of primary carbide to secondary carbide could not take place and also, this affected uniformity of Co binder and resulted in non-uniform metal matrix.

iv. Non Cryo-treated insert

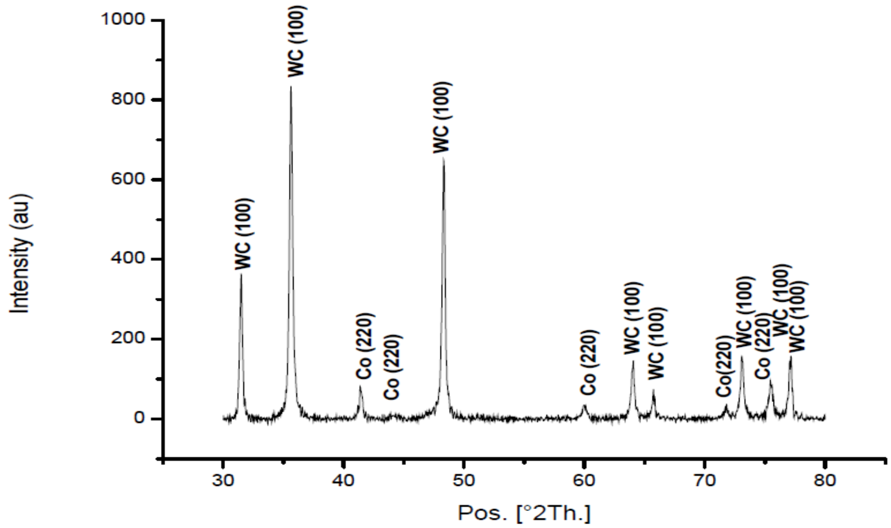


Fig. 33 XRD Profile for Non Cryo-treated insert

As this insert was taken as reference, XRD of the same showed uniform presence of WC crystal along with Co binder phase. Also, presences of some primary carbide were reported.

IV. Hardness Test Analysis

Since, due to subsequent cooling and heating of inserts, the thermal stresses are generated in WC–Co alloys as a result of the large difference between the coefficients of thermal expansion of the WC and Co-phases. The carbide phase is subjected to compressive stresses while the binder to tensile ones. The magnitude of the stresses in the cementing phase increases with decreasing cobalt content due to quenching. This causes decrease in ductility of the insert. The rapid cooling of these alloys causes compression of tungsten carbide from all sides, and an increase of compressive stresses would lead to an increase in the strength of the carbide matrix. Therefore, the strength of low-cobalt alloys as awhole gets slightly increased. There is a slight increase in the micro-hardness along with toughness due to the controlled cryogenic treatment compared to untreated WC–Co sample.

To check the effect of CT on hardness property of PVD coated and Non PVD coated insert, Vickers micro-hardness test was conducted. A load of 50 kgf was impressed on surface of insert using pyramidal diamond indenter for dwell time of 10 seconds and hardness values were tabulated as shown below.

Fig. 34 Vickers Hardness Tester

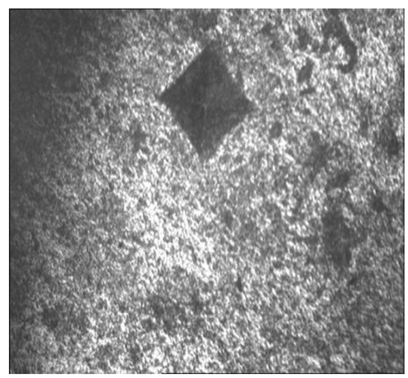


Fig. 35 Impression made by indenter on surface of insert

Table 13 Vickers Hardness Value for PVD Coated Inserts

Insert Type	**Vickers Hardness Value**
0.5 °C/min (Cryo-treated + tempered)	2332 HV 50
1.0 °C/min (Cryo-treated + tempered)	2234 HV 50
1.0 °C/min (Cryo-treated)	2284 HV 50
Non Cryo-treated insert	2170 HV 50

Table 14 Vickers Hardness Value for Non PVD Coated Inserts

Insert Type	Vickers Hardness Value
0.5 °C/min (Cryo-treated + tempered)	3595 HV 50
1.0 °C/min (Cryo-treated + tempered)	3320 HV 50
1.0 °C/min (Cryo-treated)	3494 HV 50
Non Cryo-treated insert	3239 HV 50

It was found that, when inserts were CT, hardness is increased as compared to Non CT inserts. But, it was also reported that, CT insert at 0.5 °C/min and when followed by tempering provided better improvement in hardness as compared to 1.0 °C/min (Cryo-treated + tempered) and 1.0 °C/min (Cryo-treated).

V. Conductivity Analysis

It was observed that, cryogenic treatment reduces the chemical degradation of the WC-Co matrix at higher temperatures generated while machining at higher cutting velocity. An increase in carbide grain size and grain refinement of secondary carbides along with densification of Co binder for the cryogenic treated cemented carbides increases the thermal conductivity of cemented carbide. The increase in thermal conductivity due to cryogenic treatment increases heat dissipation capacity of cutting tool and helps in decreasing the tool tip temperature, which ultimately improves tool life. Wiedemann– Franz Law states that, for all metals at not too low temperature, the ratio of the thermal conductivity to the electrical conductivity is directly proportional to the temperature with the value of the constant proportionality independent of the particular metal. Hence, a standard four probe set-up was used to study the electrical resistivity of the cutting tool inserts.

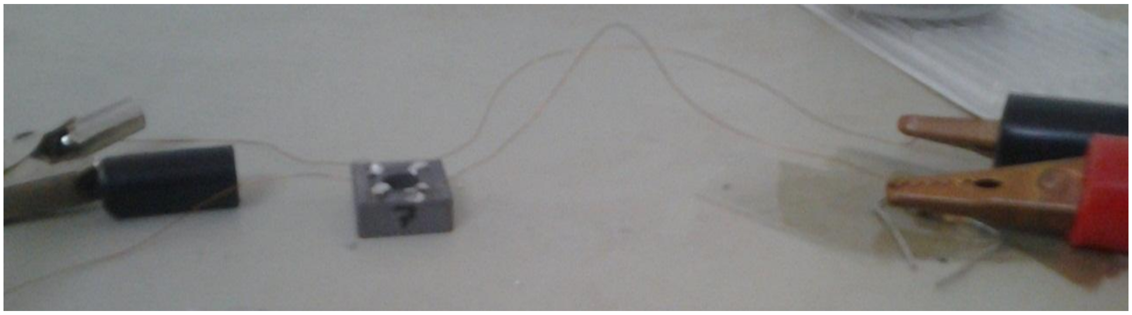


Fig. 36 Four point probe in contact with insert

Fig. 37 DC Micro-voltmeter, constant current source and PID controlled oven set up for recording voltage corresponding to current.

Table 15 Electrical conductivity of various insert

Insert type	**Conductivity (ohm^{-1}-m)**
0.5 °C/min (Cryo-treated + tempered)	2760
1.0 °C/min (Cryo-treated + tempered)	2180
1.0 °C/min (Cryo-treated)	2206
Non Cryo-treated insert	1600

It could be observed from the Table 15 that, there is an increase in electrical conductivity from untreated to deep cryo-treated inserts. Thus, there is an increase in thermal conductivity from untreated to deep cryo-treated inserts, which protect the tool tip and increases its working life.

VI. Taguchi Analysis

In order to compare performance of various CT inserts with Non CT insert, a Taguchi L_9 experimental run was designed using cutting velocity, feed rate and depth of cut as input parameters and responses were recorded as flank wear of cutting insert, surface roughness of workpiece and cutting forces during machining operation.

Table 16 Taguchi L_9 experimental run

Run	**Cutting Velocity (m/min)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**
1	50	0.04	0.1
2	50	0.05	0.2
3	50	0.06	0.3
4	70	0.04	0.2
5	70	0.05	0.3
6	70	0.06	0.1
7	90	0.04	0.3
8	90	0.05	0.1
9	90	0.06	0.2

Table 17 Response table for PVD coated inserts

Run	PVD Coated Insert																			
	0.5 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated)					Non Cryo-treated PVD Coated insert				
	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z
1	1.05	0.090	74	19	197	1.13	0.112	95	31	210	1.35	0.143	118	75	255	1.31	0.127	140	51	238
2	3.27	0.115	120	55	208	3.40	0.127	145	62	221	3.56	0.151	161	117	262	3.54	0.141	185	95	245
3	4.21	0.147	195	368	232	4.46	0.175	220	372	245	4.64	0.200	247	430	288	4.51	0.192	264	431	271
4	0.90	0.108	100	40	212	1.06	0.132	128	52	226	1.30	0.154	147	97	269	1.28	0.153	170	81	252
5	2.90	0.160	100	65	225	3.20	0.182	130	81	239	3.45	0.209	157	119	280	3.31	0.197	181	98	262
6	3.81	0.151	92	9	230	4.03	0.174	119	21	243	4.20	0.198	139	69	288	4.07	0.190	165	51	275
7	0.85	0.170	67	52	156	1.00	0.198	89	64	169	1.20	0.227	115	110	211	1.11	0.214	138	95	195
8	2.12	0.182	77	3	145	2.30	0.207	101	16	157	2.84	0.220	128	65	200	2.38	0.222	151	46	182
9	2.82	0.200	62	31	140	3.00	0.230	90	45	151	3.19	0.263	111	90	192	3.08	0.245	134	78	175

Table 18 Response table for Non PVD coated inserts

Run	**Non PVD Coated Insert**																			
	0.5 °C/min (Cryo-treated + tempered)					**1.0 °C/min (Cryo-treated + tempered)**					**1.0 °C/min (Cryo-treated)**					**Non Cryo-treated Non PVD Coatedinsert**				
	R_a	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**
1	1.26	0.152	129	61	266	1.35	0.168	148	79	278	1.62	0.215	211	128	315	1.40	0.179	189	103	299
2	3.46	0.171	181	121	276	3.59	0.189	199	134	286	3.92	0.231	255	187	327	3.74	0.221	228	174	305
3	4.46	0.210	251	457	298	4.60	0.229	263	487	312	4.95	0.261	340	532	350	4.71	0.241	306	503	335
4	1.06	0.181	162	101	281	1.20	0.211	188	119	295	1.54	0.211	228	171	333	1.37	0.218	225	153	316
5	3.20	0.223	177	121	292	3.31	0.247	191	138	308	3.77	0.261	242	182	343	3.60	0.260	235	150	330
6	4.03	0.216	153	67	295	4.13	0.234	179	81	311	4.49	0.258	231	131	348	4.25	0.250	221	132	333
7	1.00	0.230	114	118	220	1.14	0.256	145	135	232	1.49	0.288	211	182	272	1.31	0.273	183	178	251
8	2.30	0.245	128	62	216	2.41	0.244	157	75	228	2.90	0.275	229	121	269	2.60	0.265	198	96	245
9	3.00	0.262	111	90	214	3.13	0.271	146	103	224	3.70	0.310	199	150	263	3.31	0.288	183	141	239

a) **Taguchi Analysis Report**

Taguchi analysis was done in order to find the significant effect of input machining parameters i.e.cutting speed, feed rate and depth of cut on output responses i.e. surface finish of the machined work-pieces, flank wear of the cutting tool inserts and cutting forces.

Table 19 Percentage contribution chart for PVD coated inserts

Percentage Contribution		**PVD COATED INSERT**																			
		0.5 °C/min (Cryo-treated + tempered)					**1.0 °C/min (Cryo-treated + tempered)**					**1.0 °C/min (Cryo-treated)**					**Non Cryo-treated Non PVD Coated insert**				
		Output Responses																			
		R_a	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**	**R_a**	**FW**	**F_x**	**F_y**	**F_z**
Input Parameters	**Cutting Velocity**	10	65	43	26	91	10	66	41	24	92	7	63	35	26	92	11	67	36	23	91
	Feed Rate	87	28	15	18	2	86	28	17	18	2	90	24	17	19	2	85	24	17	20	2
	Depth of Cut	2	6	19	39	5	3	5	20	38	5	2	10	24	35	4	2	7	22	35	4

Table 20 Percentage contribution chart for Non PVD coated inserts

Percentage Contribution		NON PVD COATED INSERT																			
		0.5 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated + tempered)					1.0 °C/min (Cryo-treated)					Non Cryo-treated Non PVD Coated insert				
		Output Responses																			
		R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z	R_a	FW	F_x	F_y	F_z
Input Parameters	**Cutting Velocity**	10	68	48	23	93	11	66	41	23	92	7	62	34	24	92	10	63	38	22	92
	Feed Rate	86	25	14	19	2	86	20	17	18	3	90	25	18	18	3	86	23	18	21	2
	Depth of Cut	2	6	20	37	3	2	15	20	38	4	2	11	22	36	3	3	12	20	36	4

From above Taguchi analysis following observations are reported which showed that:

a. Cutting velocity affects cutting forces more than feed and depth of cut for all cases;

b. Similarly, feed rate has significant effect on surface roughness;

c. Cutting velocity has also significant effect on flank wear;

d. Feed force was mostly affected by cutting velocity, followed by depth of cut and feed rate;

e. In the case of thrust force, depth of cut was found to have significant effect followed by cutting velocity and then feed rate;

f. 0.5 °C/min (Cryo-treated + tempered) inserts showed desirable significant effect on output responses than other category of inserts (i.e. 1.0 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated), Non Cryo-treated Non PVD Coated insert);

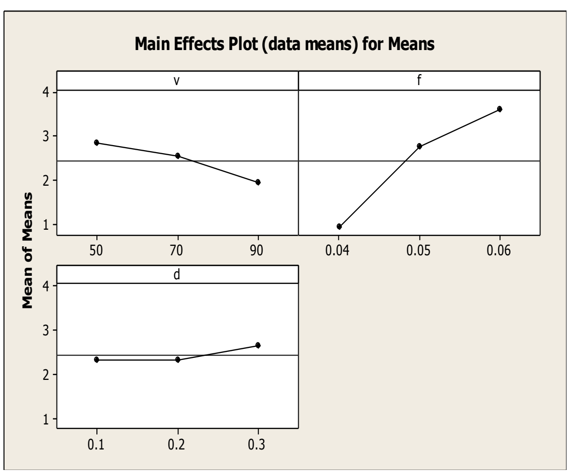


Fig. 38 Graph for surface roughness (R_a)

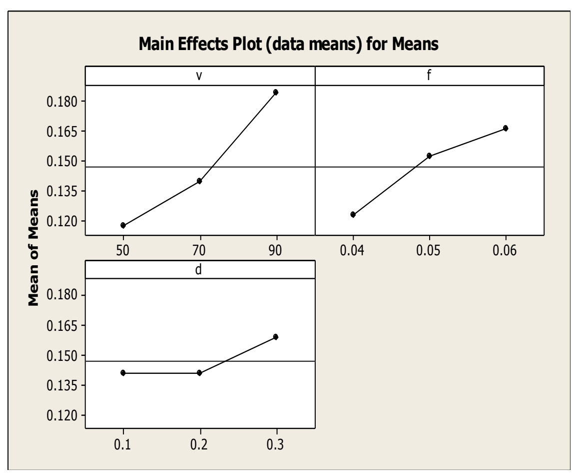


Fig. 39 Graph for flank wear (FW)

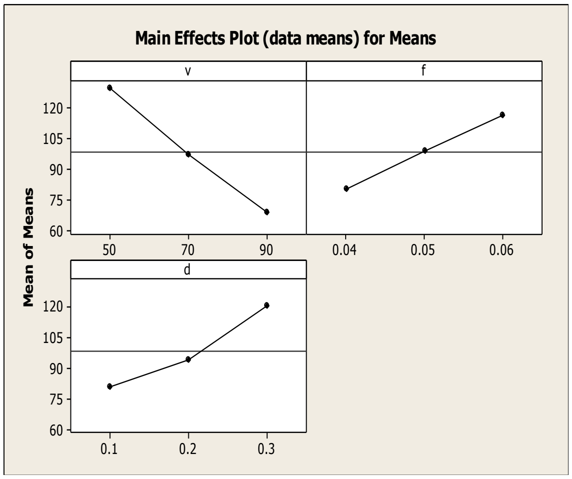


Fig. 40 Graph for feed force (F_x)

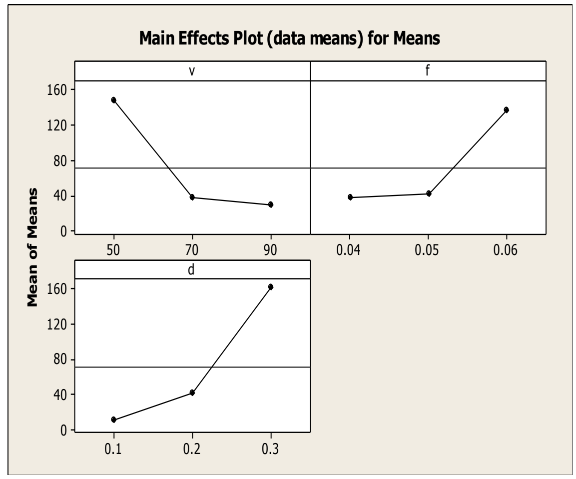


Fig. 41 Graph for thrust force (F_y)

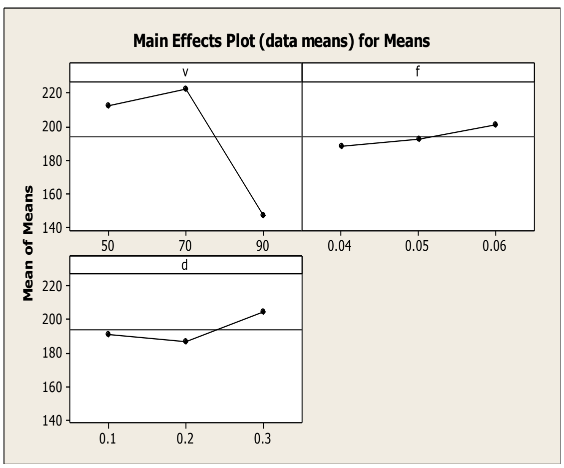


Fig. 42 Graph for cutting force (F_z)

b) Regression equation

The regression equation for surface roughness (R_a) is

$$R_a = -2.99 - 0.0228\ v + 134\ f + 1.63\ d$$

The regression equation for flank wear (FW) is

$$FW = -0.0960 + 0.00167\ v + 2.17\ f + 0.0900\ d$$

The regression equation for feed force (F_x) is

$$F_x = 75.6 - 1.53\ v + 1800\ f + 198\ d$$

The regression equation for thrust force (F_y) is

$$F_y = - 120 - 2.97 v + 4950 f + 757 d$$

The regression equation for cutting force (F_z) is

$$F_z = 264 - 1.63 v + 617 f + 68 d$$

c) Surface roughness

For all types of inserts, the surface roughness decreases as cutting velocity increases. With increase in cutting velocity, the cutting forcedecreases which lead to a minimum vibration during machining and thus lowerthe surface roughness on the workpiece. Also, it was observed that, Surface Roughness increases with increase in feed rate and depth of cut, which is basically due to increase in material removal rate and consecutive plastic deformation of workpiece.

Table 21 Surface Roughness (R_a) values for various PVD coated and Non PVD coated inserts

Insert Type	**Average Surface Roughness (R_a)**	
	PVD coated inserts	**Non PVD coated inserts**
0.5 °C/min (Cryo-treated + tempered)	2.436667	2.641111
1.0 °C/min (Cryo-treated + tempered)	2.620000	2.762222
1.0 °C/min (Cryo-treated)	2.858889	3.153333
Non Cryo-treated insert	2.732222	2.921111

From above table, it is found that, the surface roughness of the workpiece is found to be lower, when machined with 0.5 °C/min (Cryo-treated + tempered) inserts in comparison with

1.0 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated) and non Cryo-treated inserts, for both the cases of PVD coated and Non PVD coated inserts.

Due to optimum cooling rate and tempering being followed for 0.5 °C/min (Cryo-treated + tempered) insert, makes it hard and tough enough to avoid flank wear at high rate, which is due solely to presence of η-phase carbide and Co phase densification respectively. This causes the insert to maintain hardness up to a long extent and produce better surface finish than its counterpart inserts.

d) Flank wear

It can be clearly seen from graphical studies that, the flank wear continuously increasing as the cutting velocity increases. Increase in cutting speed results in concentration of high cutting temperatures at the cutting edge of the insert, due to shorter contact area at chip–tool interface. As a result the strength of the insert tip is reduced and flank wear became more during machining. Flank wear increases both with feed and depth of cut because of weakening of the insert tip at high cutting forces and higher cutting temperatures generated due to increase in the rate of plastic deformation of workpiece while machining.

Table 22 Flank wear (FW) values for various PVD coated and Non PVD coated inserts

Insert Type	**Average Flank wear (FW)**	
	PVD coated inserts	**Non PVD coated inserts**
0.5 °C/min (Cryo-treated + tempered)	0.147000	0.210000
1.0 °C/min (Cryo-treated + tempered)	0.170778	0.227667
1.0 °C/min (Cryo-treated)	0.196111	0.256667
Non Cryo-treated insert	0.186778	0.243889

While analysing flank wear for various inserts, it was reported that, the same has lowest values for 0.5 °C/min (Cryo-treated + tempered) followed by 1.0 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated) and Non Cryo-treated insert. We clearly know that, flank wear determines the tool life. Hence, 0.5 °C/min (Cryo-treated + tempered) insert have longer tool life because, of its wear resistance property developed due to the fine precipitation of η-phase carbide and uniform distribution of WC in Co binder phase in the metal matrix, when compared to other inserts.

e) Feed force

It can be clearly seen that, cutting velocity when increased causes feed force to decrease. Feed force increases with increase in depth of cut followed by feed rate. This is because, increasing depth of cut or feed rate or both, the cross-sectional area of the uncut chip and the volume of the deformed material will increase, and hence, the resistance (or forces required) for the chip formation will also increase.

Table 23 Feed force (F_x) values for various PVD coated and Non PVD coated inserts

Insert Type	**Average Feed force (F_x)**	
	PVD coated inserts	**Non PVD coated inserts**
0.5 °C/min (Cryo-treated + tempered)	98.55556	156.2222
1.0 °C/min (Cryo-treated + tempered)	124.1111	179.5556
1.0 °C/min (Cryo-treated)	187.0000	238.4444
Non Cryo-treated insert	169.7778	218.6667

f) Thrust force

Depth of cut is seemed to have maximum effect on thrust force followed by cutting velocity and feed rate. An increase in the depth of cut increases the width of uncut chip and therefore, increases the forces acting on the tool rake face and flank face both. An increase in feed rate also increases the cross-sectional area of the uncut chip and hence, increases the thrust force.

Table 24 Thrust force (F_y) values for various PVD coated and Non PVD coated inserts

Insert Type	**Average Thrust force (F_y)**	
	PVD coated inserts	**Non PVD coated inserts**
0.5 °C/min (Cryo-treated + tempered)	71.33333	133.1111
1.0 °C/min (Cryo-treated + tempered)	82.66667	150.1111
1.0 °C/min (Cryo-treated)	130.2222	198.2222
Non Cryo-treated insert	114.0000	181.1111

g) Cutting force

Graphical studies reflect that, the cutting force decreases as the cutting speed increases. This is due to the fact that, the cutting temperature is higher at higher cutting speeds, resulting in softening effect of workpiece at higher cutting speeds. Effect of variation of feed and depth of cut on cutting force indicates that, the cutting force increases when both feed and depth of cut are increased. This is due to the fact that, with the increase in feed and depth of cut, material removal rate, and hence the rate of plastic deformation increases, resulting in increase in the cutting force.

Table 25 Cutting force (F_z) values for various PVD coated and Non PVD coated inserts

Insert Type	**Average Cutting force (F_z)**	
	PVD coated inserts	**Non PVD coated inserts**
0.5 °C/min (Cryo-treated + tempered)	193.8889	262.0000
1.0 °C/min (Cryo-treated + tempered)	206.7778	274.8889
1.0 °C/min (Cryo-treated)	249.4444	313.3333
Non Cryo-treated insert	232.7778	294.7778

The cutting forces for the Cryo-treated inserts were lower when compared to non Cryo-treated inserts. This is due to less distortion of cutting edge of Cryo-treated inserts in comparison to untreated inserts.

Due to the wear resistant property of η-phase carbide and conductive nature of Co binder phase, 0.5 °C/min (Cryo-treated + tempered) showed better resistance to higher cutting forces and temperatures than other inserts.

VII. TOOL LIFE ANALYSIS

Flank wear

Wear basically determines the tool life and of all, flank wear is the most important tool wear occurring during machining operation. The flank wear is primarily due to rubbing of the tool along the workpiece surface, causing abrasive, diffusive and adhesive wear. This leads to increase in temperature, which affect the cutting tool edge as well as the workpiece surface.

As the cutting speed increases, wear increases due to two reasons:

(i) Increase in the sliding distance of cutting tool for a given time;

(ii) Increase in cutting temperatures, which leads to plastic deformation of the cutting edge.

It is seen that, at the initial stage of the machining process, flank wear rate of the inserts is least at all cutting speeds. This is due to multi-layered coatings on tool tips. As machining proceeds, layer by layer coatings on tool tips wear out gradually. Finally, a rapid flank wear is noticed. This is possibly due to a complete wear out of the multi-layered coating material, and the substrate of the tool being in direct contact with workpiece during machining.

Since main objective of this project work was to evaluate performance of CT insert treated at different cryogenic cooling rate (i.e. 0.5 C/min (CT+T), 1.0 C/min (CT+T), 1.0 C/min (CT)) and compare its performance with non-CT inserts, flank wear of insert occurring while turning was used as an important tool in analysis of result. Lesser the flank wear, better is the tool life of the insert. So, when turning was performed at higher speed, time of machining was increased accordingly. Feed rate (0.05 mm/rev) and depth of cut (0.1mm) was held constant during entire course of turning operation.

Table 26 Flank wear experimental layout

Time (min)	Speed (m/min)
1	90
2	120
3	150

Flank wear for PVD coated inserts

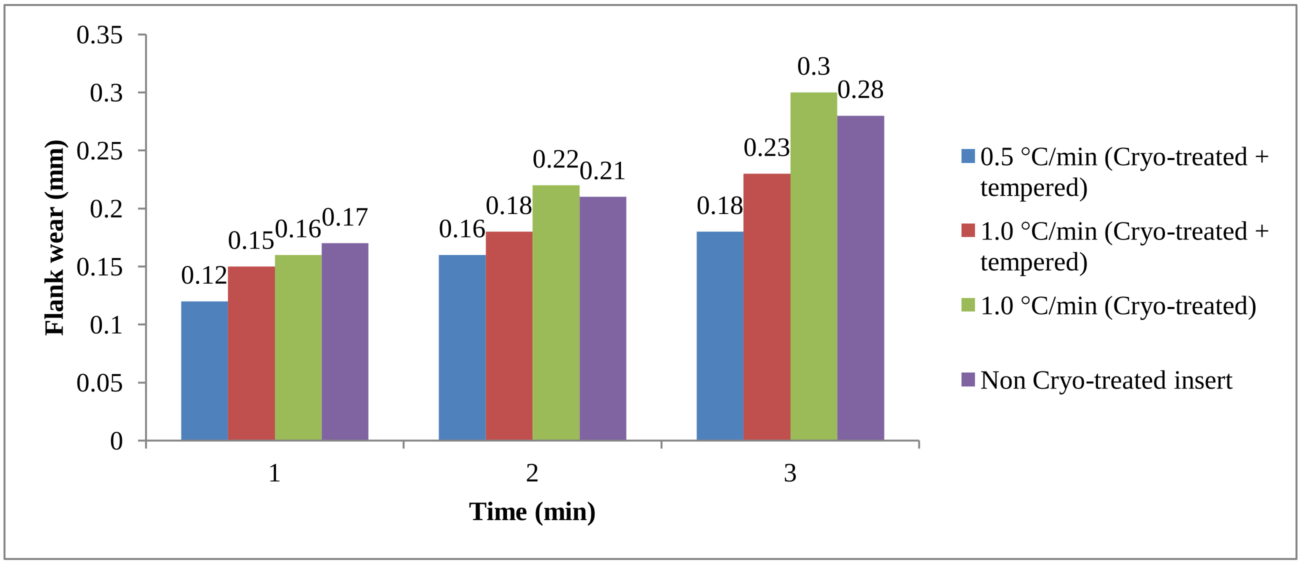


Fig. 43 Graph for flank wear vs. time for PVD coated inserts

Flank wear for Non PVD coated inserts

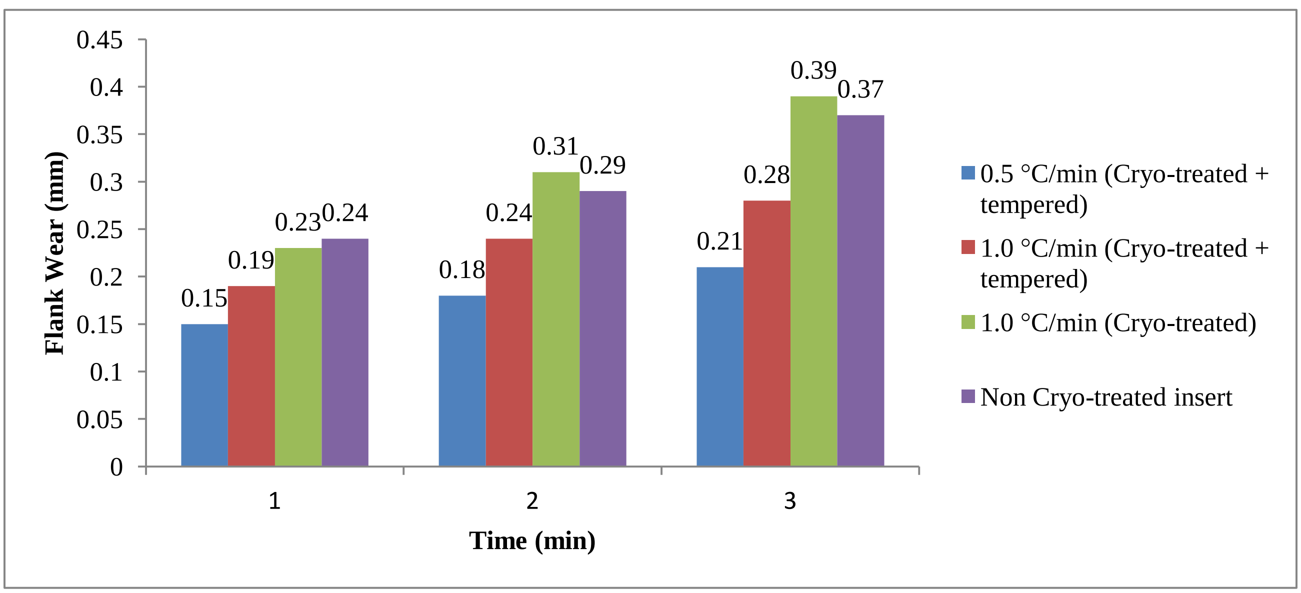


Fig. 44 Graph for flank wear vs. time for Non PVD coated inserts

Graphical analyses for variation of flank wear with time along with increasing cutting velocity, showed that, minimum flank wear was observed in the case of 0.5 °C/min (Cryo-treated + tempered) and maximum flank wear was reported for Non Cryo-treated Coated insert, both for PVD coated and Non PVD coated carbide insert. But at the same time, only CT of inserts, when not followed by tempering, could lead to chipping effect (i.e. 1.0 °C/min (Cryo-treated)) and result in reduced tool life, due increased flank wear. Also, it was observed that flank wear increases with increasing in cutting velocity and has significant effect on the tool life.

VIII. Modeling and Simulation

FEM modeling and simulation of orthogonal cutting of AISI 304 Stainless steel by carbide insert is studied by using ABAQUS 6.10 software. The simulation model utilizes the Arbirary Lagrangian Eulerian method (ALE) method in simulating plastic flow around the round edge of the cutting tool and eliminates the need for chip separation criteria. Johnson- Cook work material model is used for elastic plastic work deformations. The simulation results include stress and temperature distributions at the tool-chip interface.

Table 27 Parameters for Tool-workpiece model

Properties	**Carbide Tool**	**AISI 304 Stainless Steel Workpiece**
Coefficient of thermal expansion	4.5 µm/m°C	11 µm /m°C
Density	15 g/cm³	7.8 g/cm³
Poisson’s Ratio	0.2	0.33
Specific heat	200 J/kg/°C	430 J/kg/°C

Thermal conductivity	45 W/m°C	48 W/m°C
Young's Modulus	796 GPa	210 GPa

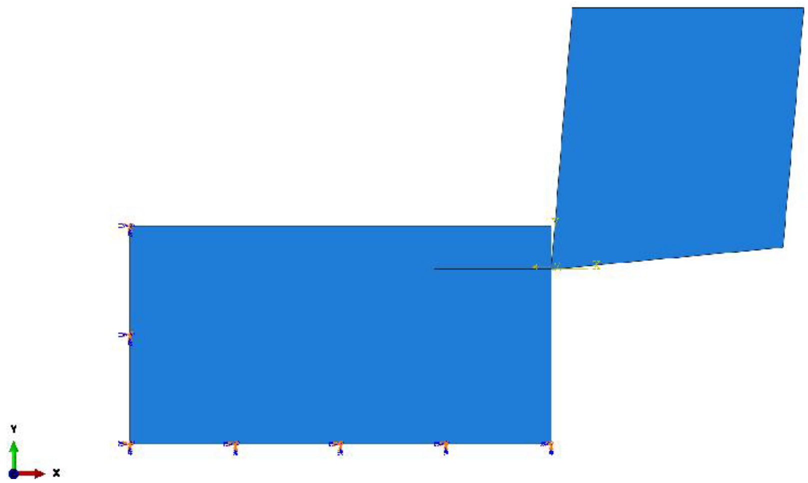


Fig. 45 Tool-workpiece model

Stress Analysis

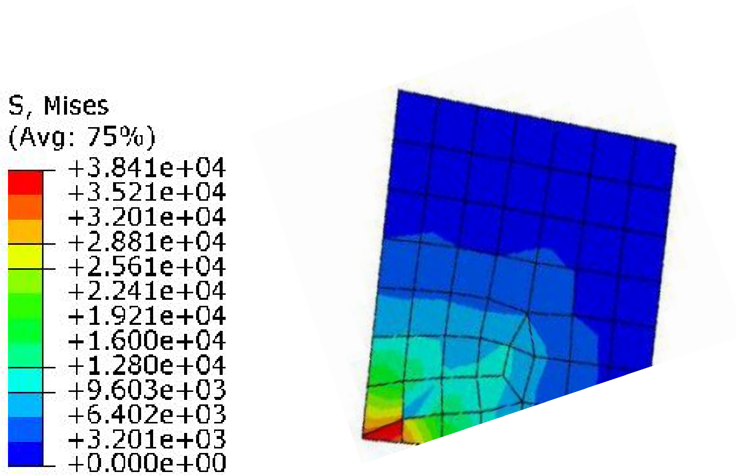


Fig. 46 Stress distribution

Stress analysis of the model showed that, maximum stress is produced at the tool tip during shearing of material.

Temperature Analysis

Temperature analysis of the model showed that, maximum temperature is produced at the tool-chip interface and is being carried away by the chip.

Conclusion

The concept of cryogenic treatment (i.e. treatment at -190 °C) of inserts was being extended by subjecting the inserts to different cooling and warming rates (i.e. 0.5 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated + tempered), 1.0 °C/min (Cryo-treated)) and evaluate the performance by comparing with non-CT inserts using turning operation. Some of the major conclusion that was drawn after various analyses is as follows:

1) SEM, EDS and XRD analysis of CT inserts treated at 0.5 °C/min showed the presence of fine precipitates of η-phase carbides along with WC uniformity in metal matrix along with Co binder phase densification; when compared to inserts treated at other cooling rates and non-CT insert. This proves that CT and tempering at 0.5 °C/min (20-30 °C/hr.) improves hardness along with improvement in toughness of inserts.
2) Treatment at 1.0 °C/min or above and followed by tempering showed that inserts develop brittleness and hardness, with decrease in toughness as % of Co binder phase decreases due to high rate of cooling and warming. This also affects the precipitation of η-phase.
3) Only CT of inserts at 0.5 °C/min or above produces catastrophic results as tool becomes fragile and is easily prone to chipping as WC % increases and Co % decreases with no or less η-phase grain refinement.
4) After all set of inserts were being turned using AISI 304 Stainless steel and output responses were recorded in the form of cutting forces, flank wear and surface roughness;

it was found that, CT inserts at 0.5 °C/min and followed by tempering, proved better than other category of inserts.

5) Taguchi analysis was used to check the significant effect of input parameters on responses and ANOVA table was created, which showed that:
    - Cutting velocity affects cutting forces more than feed and depth of cut;
    - Feed rate has significant effect on surface roughness;
    - Feed force was mostly affected by cutting velocity, followed by depth of cut and feed rate;
    - In the case of thrust force, depth of cut was found to have significant effect followed by cutting velocity and then feed rate;
    - Cutting velocity has also significant effect on flank wear. This was also validated with tool life analysis experiment which supported Taguchi result.
6) Conductivity test showed an increase in electrical conductivity from untreated to deep cryo-treated inserts. Thus, there is an increase in thermal conductivity from untreated to deep cryo-treated inserts, which protect the tool tip from high temperature and increases its working life.
7) Hardness test proved that, when inserts were CT, hardness is increased as compared to Non CT inserts. But, it was also reported that, CT insert at 0.5 °C/min and when followed by tempering provided better improvement in hardness as compared to 1.0 °C/min (Cryo-treated + tempered) and 1.0 °C/min (Cryo-treated).
8) Chip morphology study reported continuous chip formation for 0.5 °C/min (Cryo-treated + tempered) insert and 1.0 °C/min (Cryo-treated + tempered); continuous chip with built up edge for non CT insert, while 1.0 °C/min (Cryo-treated) produced discontinuous chip.

9) CT when combined with tempering process results in releases of residual stress and improve the ductility of inserts which directly increases toughness property. Hence, CT should be followed by tempering in order to avoid brittle fracture of cutting insert

10) Tool life analysis was based on flank wear study, which proved that CT inserts provide long run than non-CT inserts, which is mainly due to Co binder densification which develops ductility and conductivity nature and this causes heat generated at tool chip interface to be easily carried away without affecting the inserts tip and improves tool life.

11) CT inserts provide better surface finish, lower cutting forces and less flank wear in comparison with non-CT inserts, which can be attributed to the reason that, micro-structural grain rearrangement and refinement takes place due to CT and tempering respectively.

12) Carbide population increases when exposed to critical temperature and they form into fine particles which are homogeneously distributed. This fine carbide improves wear resistance and have low co-efficient of friction. This phenomenon only occurs only when inserts are subjected to tempering after CT is over. Hence, CT inserts have added advantage of both hardness and toughness over non CT inserts.

13) At last but not the least, since CT when accompanied with tempering results in improved tool life and is single step process, which need not to be done again and again as in case of coating process; the CT tool can be used again and again after successive regrinding and hence, is a cost effective and time saving process. This leads to increase in productivity run and is a promising technique for eco-friendly machining in industrial arena and further research in this area holds brighter results.

Future work

Many useful benefits of CT have been reported by the researchers, but due to complexity of the process, change in mechanism is still unpredictable. Further investigation requires a critical study of parameters like cooling rate, soaking duration, warming rate and tempering cycle in order to optimize the process for various materials. Effect of CT on the thermo-mechanical fatigue behaviour of different material could be an interesting research field. CT should be applied to non ferrous alloys like polymers and composites in order to study changes in their mechanical properties. FEA modeling and simulation of orthogonal cutting can be extended for determination of cutting forces in order to validate with experimental results. For sustainable production, concept of cryogenic machining should be implemented to shop floor level.

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